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SCIENCE AND TECHNOLOGY

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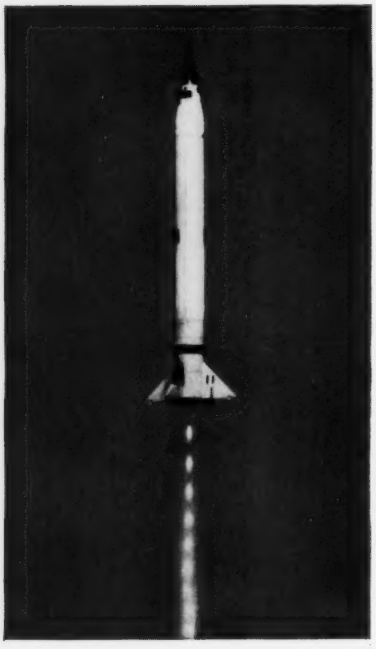

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The Shot to be Seen Around the World

THE command to hold the presses for a late news break has never before been issued by the editors of this JOURNAL. The reason is a simple one: this JOURNAL is not a news magazine and we make no effort to record events as they happen. If it is inconvenient to interrupt publication to get a late report into the news section of a particular issue, we calmly postpone the item until the next one. But something big has just shaken us off course, and we felt compelled to remove the standard first page of this issue to report the event.

An announcement of far-reaching significance was made at the White House at 1:30 p.m., July 29, 1955: Within three and one half years the United States will launch an earth satellite. This shot to be seen by all mankind will herald not a bloody conflict but peaceful and constructive collaboration on an international scale in the exploration of extraterrestrial space.

Although many aspects of the project remain to be settled, the principal facts as revealed to the press are these. There is to be a series of launchings in the earth satellite vehicle (ESV) program, the first to occur in the period from July 1957 to December 1958, in order to fit into the research effort of the International Geophysical Year (IGY). The so-called bird will weigh about 100 pounds and will be of the order of one to two feet in diameter; but it is obvious that the size and shape might vary considerably, depending on the objective of the particular shot. The first bird might be merely an empty sphere designed only to reveal the atmospheric density at the outer edge of the atmosphere; later shots will probably contain electronic tracking and telemetering equipment along with scientific instrumentation.

The orbits will lie about 200 to 300 miles above the earth's surface, but the particular firing directions are not revealed. Since observations are to be made from stations along the way, the first launchings may very well take place from an established long-range proving ground, such as that off the Florida coast. Once the bird is in free flight, its orientation and flight path will no longer be controllable from the ground. Launching will be accomplished by multistage rocket, the precise number of stages not revealed (perhaps not yet settled). The orbital period will be about 90 minutes, and the bird may remain aloft for a period of days or possibly months, depending on the particular orbit and the still unmeasured atmospheric density at these altitudes. As the orbit decays, the bird will gradually penetrate the atmosphere where it is expected to destroy itself by heat.

The National Research Council, as the research agency of the National Academy of Sciences, will cooperate with the National Science Foundation in sponsoring the scientific researches that will be made with the ESV. The Department of Defense will provide the launching rockets, the firing and observation sites, and will handle all aspects of the launchings. The scientific experiments are expected to deal with the structure of the outer atmosphere, characteristics of the magnetic field of the earth, solar radiation, and cosmic rays. The NRC-NSF researches will be unclassified from the security standpoint, and this includes the design of the bird, its instrumentation, and the time and location of launching. Cooperation in these researches has been invited of all countries participating in the IGY. The phase handled by the Defense Department will be classified, at least for the present, presumably because of its close connection with techniques involved in the intercontinental ballistic missile program. The cost of the NRC-NSF research in the first group of birds will be about $10,000,000; the cost of the Defense Department's rocket launchings has not been revealed.

According to the President's statement, none of the birds will be designed to perform any military functions. No earth-scanning equipment or bomb-dropping mechanisms are contemplated or even considered feasible. Finally, it was clearly stated that only a rash optimist would conclude that manned space flight is soon to take place. Nothing could be further from the facts.

The proposal to develop an ESV has been gathering momentum ever since the conclusion of World War II, when it was realized that the basic techniques were at hand, or nearly so. That serious study of the ESV was under way was first revealed by Secretary of Defense James V. Forrestal on December 29, 1948. Earth satellites for scientific research were urged by the Special Committee for the International Geophysical Year at its meeting in Rome, September 30 to October 4, 1954, as an outgrowth of geophysical research planning that began about 1950. Before this meeting, similar resolutions had been adopted by the International Scientific Radio Union and the International Union of Geodesy and Geophysics. An extensive technical report on "The Utility of an Artificial Unmanned Earth Satellite" was prepared by the ARS Space Flight Committee and submitted on November 24, 1954, to the ARS Membership (see JET PROPULSION, February 1955, p. 71). This report, with affirmative recommendations of the ARS Board of Directors, was subsequently submitted to the National Science Foundation.

The United States' decision to undertake the ESV scientific research program was a direct response to the resolution of the Special Committee for the IGY, and the United States national committee was authorized to inform the participating groups of other countries of this decision. Although the ARS report and recommendations undoubtedly helped to influence the NSF in its thinking, as did the resolutions of other societies, the strongest factor was probably the favorable position of the Department of Defense. As an intermediate objective in the longer range Atlas program, an earth satellite vehicle project may have seemed quite attractive: it avoids completely the difficult hypersonic reentry problem; the smaller payload means smaller rockets, although some of the same hardware might be used later for the ICBM; the required guidance accuracy is less severe; and the necessary extra speed is really not much, perhaps only 2000 to 5000 ft/sec more. Finally, it is not necessary to provide a safe target area at a remote location to dispose of the missile—it will literally be thrown away.

According to the press, disagreement has arisen between several prominent Congressional leaders and the Administration on the issue of security. The White House announcement stated that steps would be taken to acquaint all forty nations (including the USSR) participating in the IGY with the details of the scientific investigations and that their cooperation would be invited. The Congressional leaders who have questioned this open policy argue that, since we are doing the job alone with our own funds, we ought to keep the results classified.

On this issue it appears to us that the Administration's position is justified, since the most important piece of information from the military standpoint cannot be concealed anyhow; namely, the density of the atmosphere as revealed by the deceleration of the bird. Anyone can follow its trajectory with a transit and figure out the drag. Moreover, there is a long series of precedents for such security treatment. The pattern is similar to that of the upper atmosphere research programs conducted up to now with V-2 rockets, Vikings, and Aerobees, in which some or all of the rocket apparatus and launching techniques have remained classified, while the scientific results, for the most part, have been openly published.

Back of the decision not to classify the bird may be a question of international diplomacy on which we can only speculate. To send such a vehicle hurtling over the "air spaces" of the various countries of the world without disclosing its contents in detail may very well arouse objections that cannot be readily dismissed. At the present moment, news reports from the USSR indicate that the open approach of the President has won the Russians over to a position of acceptance of the project and a tentative willingness to cooperate. If the USSR adopts this favorable attitude, it is likely that others will follow suit.

Whether the Russians' own satellite project is planned to achieve its objective at a similar early date has not been revealed. The only definite information available is that a scientific committee under Prof. P. Kapitza has been set up to devise a satellite similar to that described at the White House. This appeared as a news announcement in *Evening Moscow* on April 15, 1955.

We cannot imagine anything more exciting than to look up and see through our binoculars, just before sunrise or just after sunset on some not too distant day, the brilliant point of light in the sky that will represent a new astronomical body created by man. We expect to be deeply moved.

Martin Summerfield
Editor-in-Chief

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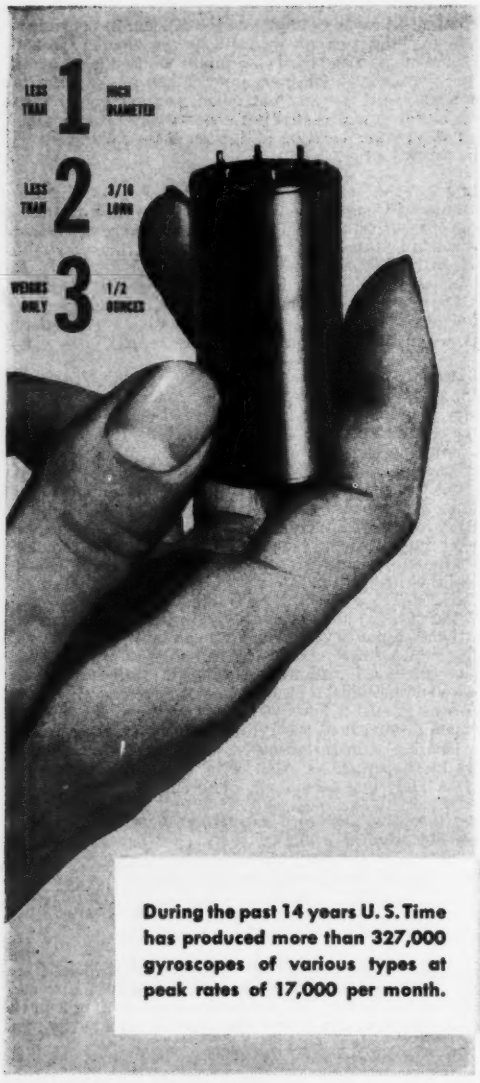

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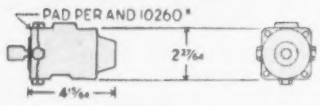

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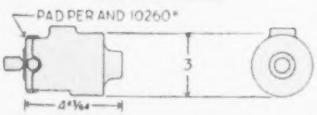

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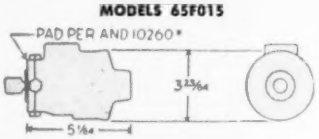

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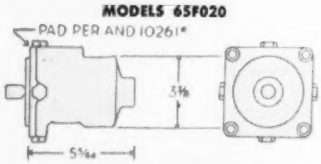

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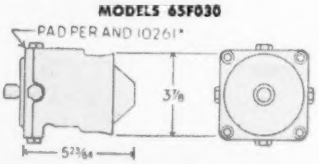

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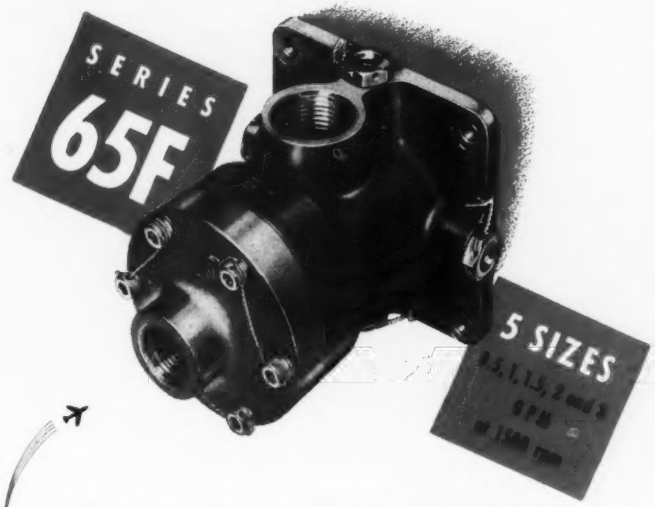

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Guided Missiles: vanes, skin protection, motor components.

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Gas Turbines: inner combustion chamber lining, cross fire tube lining, flap nozzle coating, housing and shroud ring insulation.

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Other Norton Products

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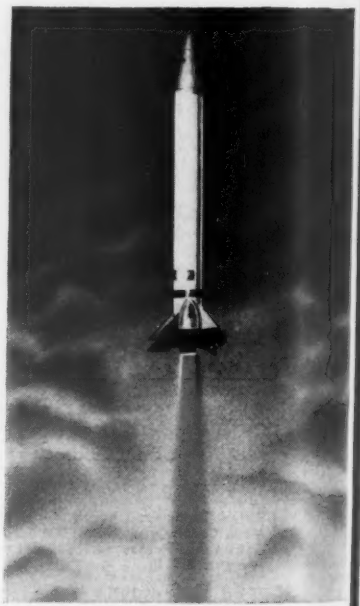
For further information on Norton products for reaction motors — or for other applications — write, mentioning your requirements, to NORTON COMPANY, *639* New Bond Street, Worcester 6, Mass.



In Rockets, Jet Planes and Guided Missiles, Norton products for reaction motors — ROKIDE "A" Aluminum Oxide Coating, ROKIDE "C" Silicon Carbide Coating and CRYSTOLON "N" Silicon Carbide Monolithic Bodies — are used for many applications.

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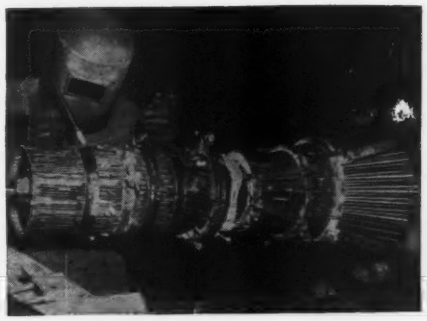

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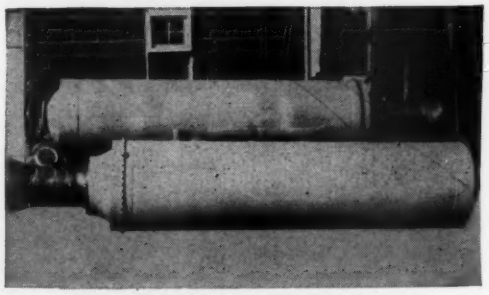

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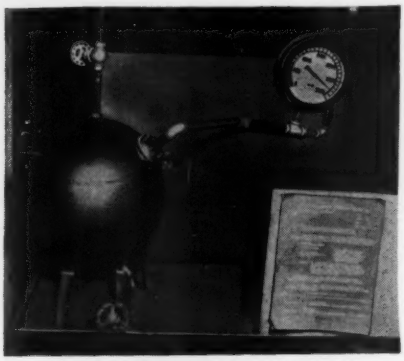

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REASON NO. 2—PROVED ABILITY. These same men actually helped to pioneer modern U.S. rocket engine activity, took part in over 67 German V-2 test flights after WW II. They have designed bi-liquid, liquid-solid, solid and ramjet propulsion systems. They provided the engine for the first large rocket in the Western Hemisphere, developed another with one of the highest specific impulses ever achieved.

REASON NO. 3—ADVANCED NEW FACILITIES ARE NOW AT THEIR DISPOSAL. General Electric is carrying on a $100 million research and development program on combustion, materials, and components of powerplants for aircraft and missiles. And the rocket engine staff now has access to development facilities such as the AGT Materials Laboratory and the AGT Component Development Laboratory at Cincinnati.

REASON NO. 4—FIRM SUPPORT OF GENERAL ELECTRIC ORGANIZATION. The entire G-E Aircraft Gas Turbine Division with its production capability and G.E.'s nationwide defense sales and service chain now support the design and development of G-E rocket engines. Add up the total. If you would like further information, contact a G-E Aircraft Specialist via your nearest G-E Apparatus Sales Office.

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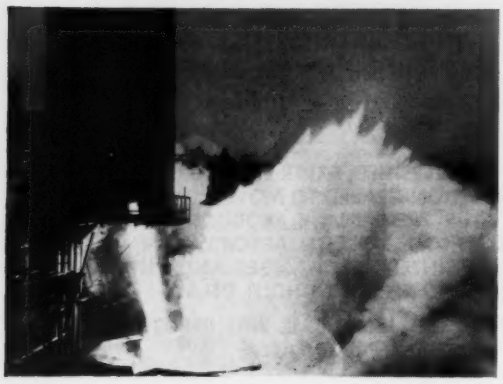
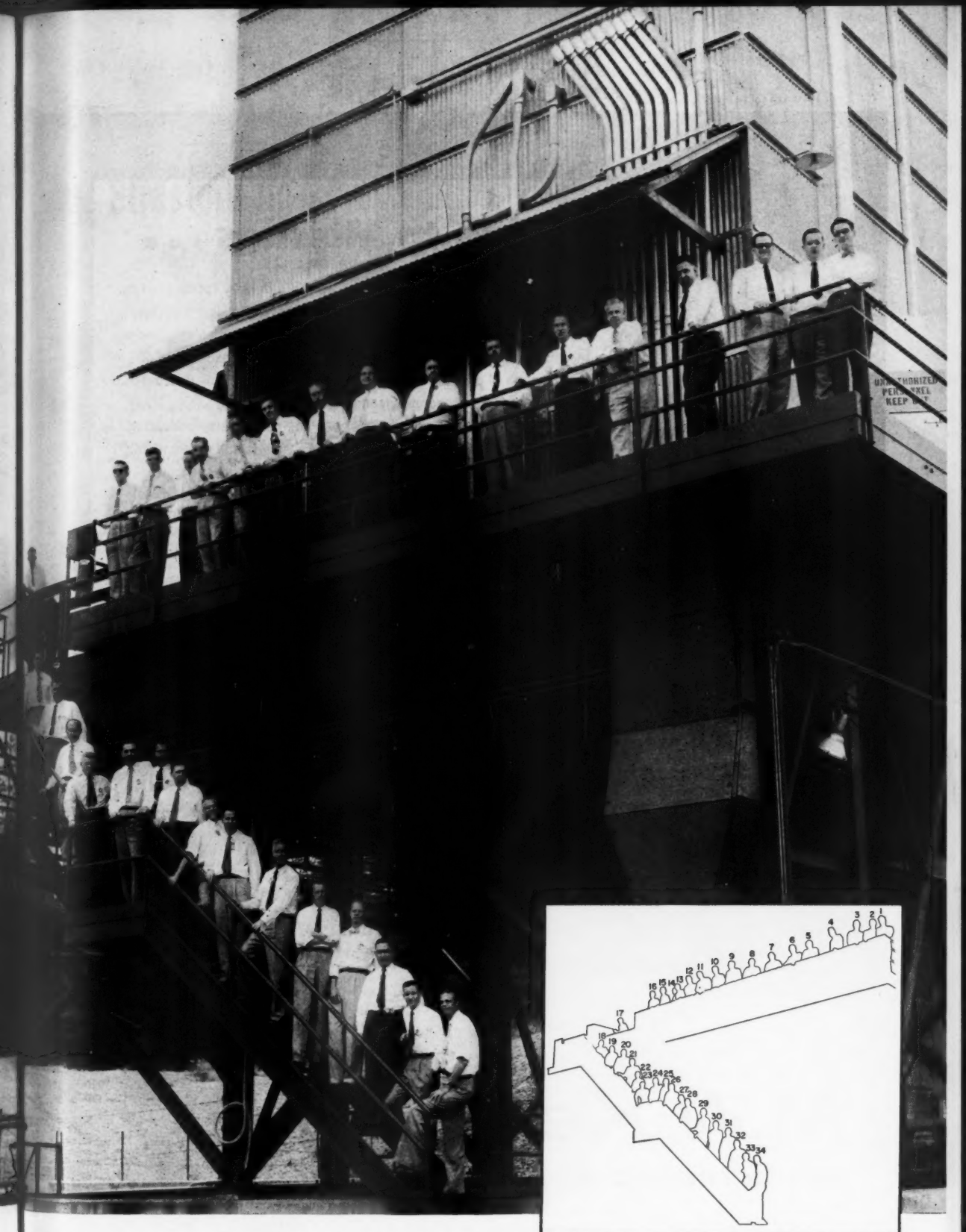
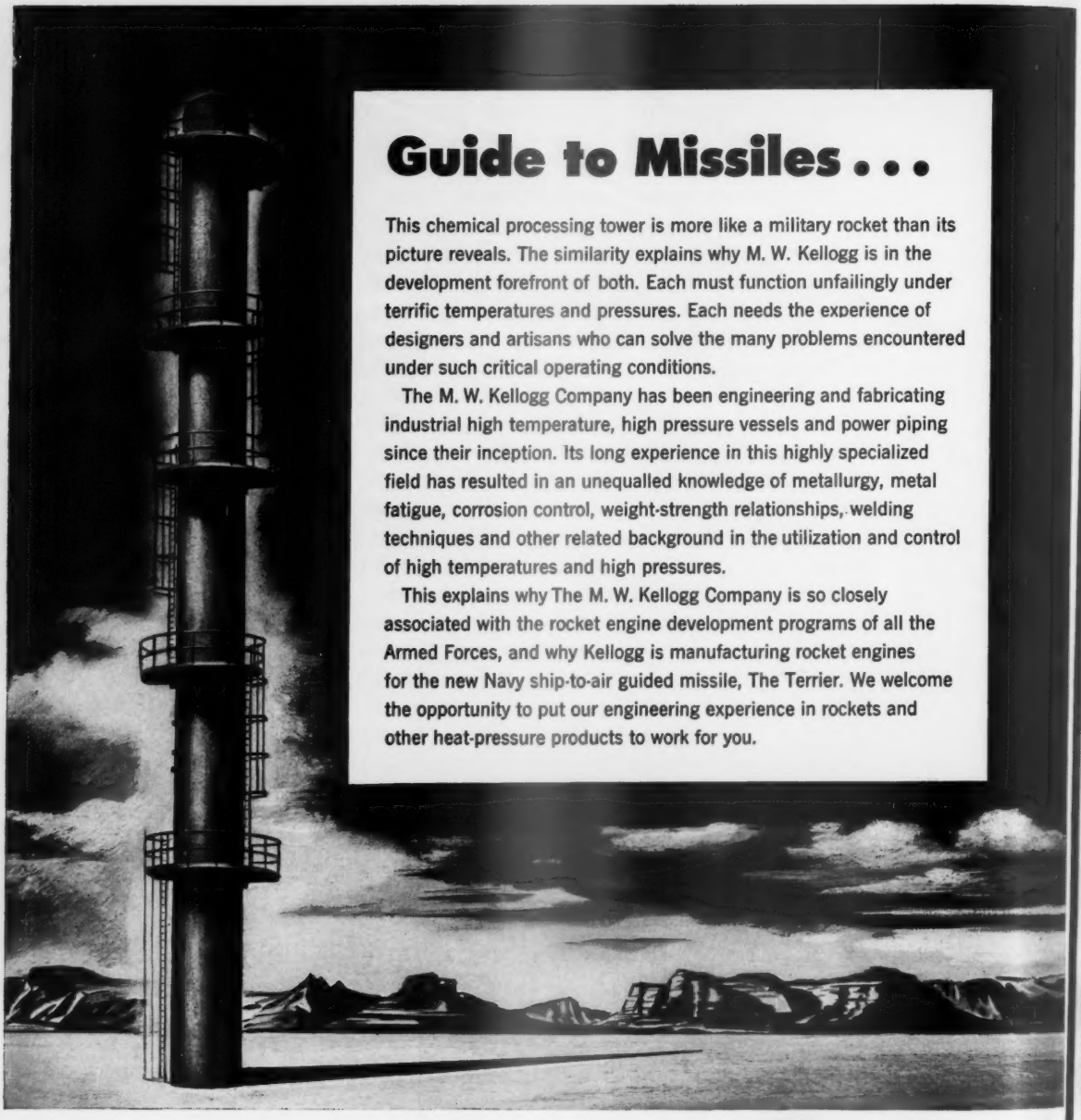


Advanced rocket engine undergoes trial at U.S. Army's Malta Test Station. The first large rocket static test station in the U.S., Malta has highly versatile facilities. Complete instrumentation gives G-E engineers extensive information on engine performance in static tests.

"Consolidating our jet and rocket engine design, development, and production capabilities within AGT is allowing us to make rapid strides in the rocket field," according to Vice President C. W. La Pierre, shown here (left) with G-E President R. J. Cordiner.



Over eight years average experience is the record of these G-E propulsion engineers, shown above at the Malta, N. Y., Rocket Test Station. **1.** T. C. Jenkins. **2.** H. M. Weber. **3.** R. Davidson, **4.** F. E. Schultz. **5.** E. H. Hull. **6.** D. Cochran, Manager, Aircraft Gas Turbine Development Department. **7.** T. S. Teague. **8.** H. C. Aikens. **9.** P. L. Duncan. **10.** J. H. Burnham. **11.** J. F. Whitbeck. **12.** W. S. Kleczek. **13.** F. J. Walker. **14.** J. Annable. **15.** G. S. Emmons. **16.** P. Gray. **17.** F. W. Crimp. **18.** J. A. Cote. **19.** A. J. Orsino. **20.** R. J. Kazyaka. **21.** G. L. McPherson. **22.** R. J. Bernadine. **23.** C. E. Rugh. **24.** L. Cherry. **25.** C. P. Beauchamp. **26.** R. B. Johnson. **27.** B. E. Sells. **28.** C. G. Dibble. **29.** B. W. Bruckman. **30.** J. N. Krebs. **31.** E. E. Paulson. **32.** Z. O. Sheldon. **33.** D. R. Messina. **34.** E. I. Finger.



Guide to Missiles . . .

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The M. W. Kellogg Company has been engineering and fabricating industrial high temperature, high pressure vessels and power piping since their inception. Its long experience in this highly specialized field has resulted in an unequalled knowledge of metallurgy, metal fatigue, corrosion control, weight-strength relationships, welding techniques and other related background in the utilization and control of high temperatures and high pressures.

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The Structure and Propagation Mechanism of Turbulent Flames in High Speed Flow

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Rational design of ramjet-type combustors requires knowledge of the mechanism of propagation of turbulent flames in high speed flow, and this in turn must rest on information concerning the internal physical structure of such flames. Recent theories of the propagation of turbulent flames are all based on the hypothesis that a turbulent flame is internally a highly wrinkled, perhaps disconnected, laminar flame, fluctuating rapidly at random within the visible contour of the turbulent flame brush. The experimental evidence for such a model has been scant and inconclusive. Experiments reported in this paper, which were designed to test the validity of the "fluctuating laminar flame" model, led to results that cannot be reconciled with it. Instead, the results indicate that the turbulent flame is really a zone of reaction distributed in depth, and that laminar flame sheets do not exist in this zone to any appreciable degree. A theory based on a "distributed reaction zone" model seems to explain with fair success the measured values of turbulent flame speed. These conclusions apply particularly to flames with high intensity turbulence.

Nomenclature

c_p = specific heat of gas mixture
d = flame zone thickness
e = fraction of reactant converted to product
(de/dt) = local rate of reaction
m = mass flow per unit flame area
S = flame speed
T = absolute temperature
v' = turbulent velocity component normal to flame surface
ϵ = turbulent diffusivity
λ = thermal conductivity
ν = kinematic viscosity
ρ = gas density
θ = fractional temperature rise

Subscripts

L = laminar flame
T = turbulent flame

Introduction

THE study of high intensity turbulent flames has specific practical value because of the occurrence of such flames in ramjets, gas turbines, and other jet propulsion devices. It has broad scientific significance because such flames represent an interesting example of interaction between fluid mechanical processes and chemical reaction. In a general way, it is well known that the intense mixing developed in a flame zone by turbulence tends to shorten the combustion region and thereby permits the utilization of compact combustors. However, it is not yet possible to predict with accuracy the increase in the over-all rate of reaction produced by turbulence, or more specifically, the increase in the effective speed of flame propagation caused by turbulence. Any such prediction will have to be based on knowledge of the physical and chemical processes that occur in a turbulent flame. It is to clarify these processes that the present investigation was undertaken.

Stimulated by the early theoretical developments of Damkohler (1)[5] and Schelkin (2), recent theories of the rate of propagation of turbulent flames have been based on the assumption that the flame zone is a region in which the combustible mixture is burned through the agency of laminar flames, that these laminar flame surfaces move about in the thick flame brush in random fashion, and that the augmentation of the burning rate arises from the enlargement of flame area due to severe wrinkling of the flame surface. The divergence between the several papers that have been written recently on the subject (3, 4, 5) stems mainly from the different statistical arguments employed to relate the flame area increase to the turbulence parameters.[6]

Thus, Damkohler and Schelkin have derived relationships of this kind

$$\frac{S_T}{S_L} = \sqrt{1 + \alpha \left(\frac{v'}{S_L}\right)^2} \quad \ldots\ldots\ldots\ldots [1]$$

For high intensity turbulence, this equation reduces to the simple statement

$$S_T \approx v' \quad \ldots\ldots\ldots\ldots [2]$$

The parameter α enters from geometric considerations of the shape of the distortions of the laminar flame surface, and has a value of the order of unity.

Presented at the ARS Ninth Annual Convention, New York, N. Y., November 30, 1954.

This paper is based on experiments carried out by the three junior authors in partial fulfillment of the requirements for the M.S.E. degree. A brief disclosure of some of the results described in this paper appeared as a Technical Note in JET PROPULSION, vol. 24, 1954, p. 254.

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[5] Numbers in parentheses indicate References at end of paper.

[6] A recent theory that also uses the wrinkled flame model to describe the flow through a turbulent flame is given in (24).

The equation derived by Karlovitz has the following form for the case of high intensity turbulence, that is, v' greater than S_L

$$\frac{S_T}{S_L} = 1 + \sqrt{\frac{2v'}{S_L}} \quad \ldots\ldots\ldots\ldots\ldots\ldots [3]$$

Measurements of turbulent flame speed by Wright (6) have been found to agree fairly well with Equation [2], in which v' was identified as the turbulent component of velocity in the approach flow. However, measurements of flame speed by Bollinger and Williams (7) could not be correlated by any of these theories; the dependence on mean stream velocity and mixture ratio appeared to be more complicated than the simple predictions implied by these equations. Data on turbulent flame speeds reported by Karlovitz (3) did not agree with Equation [3] when v' was evaluated in the approach flow. By a theoretical argument that rests on faulty fluid mechanics (in our opinion), Karlovitz made an estimate of the "flame-generated" turbulence, and by means of this larger value of v' a better fit with Equation [3] was obtained. Recent experiments by Wohl (5) showed that the turbulent flame speed did not follow any of these simple equations, and, in particular, that the effect of mixture ratio was much more pronounced than had been expected.

It should be observed that all of these theoretical attempts at an equation for turbulent flame speed assume that the local propagation characteristics of the hypothetical fluctuating laminar flame are unchanged. Nevertheless, some suspicion that the turbulence might affect the detailed mechanism of burning, either by amplifying the local transport rates or by modifying the reaction kinetics, has persisted since the early publication by Damkohler (1). On the hypothesis that "small-scale" turbulence would amplify the transport rate but *not* affect the reaction kinetics, Damkohler proposed the relationship

$$\frac{S_T}{S_L} = \sqrt{\frac{\epsilon}{\nu}} \quad \ldots\ldots\ldots\ldots\ldots\ldots [4]$$

Wohl and others have pointed out the obvious fact that small-scale turbulence exists even in the presence of large-scale turbulence, and that modification of the normal burning velocity might therefore occur with any scale of turbulence. The question of the effect of turbulence on the reaction mechanism has been raised recently by Gaydon and Wolfhard (8) and by Clark and Bittker (9), both of whom investigated the spectral intensity distribution of the light emitted by turbulent flames, but their results were inconclusive and mutually contradictory. Von Kármán and Marble, in 1952, expressed the opinion that the interpretation of the phenomena in the turbulent combustion zone as a superposition of oscillating wrinkled laminar flame fronts was doubtful, particularly for fully developed turbulence, and that the visual observations showing something similar probably referred to a transition state (11).

If these suspicions turn out to be justified, it will be necessary to discard the fluctuating laminar flame model of the turbulent flame. In spite of certain ionization fluctuation measurements by Karlovitz (22), which were interpreted as supporting evidence, there is no convincing proof of the model. Furthermore, it has been reported by Longwell (10) that in certain ramjet-type burners, the volumetric intensity of combustion is so high that the turbulent flame brush could not possibly contain enough laminar flame sheets to provide the laminar flame area needed to account for the observed combustion intensity.

Early in 1953, the senior author of this paper initiated a series of experiments designed to test the validity of the wrinkled laminar flame model, with the hope of settling the controversy. The very first results, described later under the heading of filtered photographs, contradicted this model, and there emerged instead a more reasonable physical description, namely, that the turbulent flame is a region of distributed reactions occurring in sequence along the flow lines with smooth spatial variations of the time-average values of composition and temperature, somewhat like a thickened laminar flame. It was believed that this model would apply particularly to flames with high intensity turbulence. The reaction zone would be characterized by special reaction rate functions (depending on the turbulence) which would govern the transition from unburned fuel and air on the cold side, through the region of short-life intermediates and partial combustion, to the region of stable products on the hot side. On this basis, it is possible to derive an expression for the turbulent flame speed.

The Burner and Test Equipment

The first matter to be investigated was the physical and chemical structure of the turbulent flame zone in order to establish a sound basis for theoretical analysis. Following the investigation of flame structure, the turbulent flame speed was to be measured for comparison with the theory.

It seemed logical to carry out the experiments on flame structure with a turbulent flame as nearly two-dimensional as possible. This was particularly necessary for the spectral traverses and for measurements of flame speed and flame thickness. A schematic drawing of the burner is shown in Fig. 1

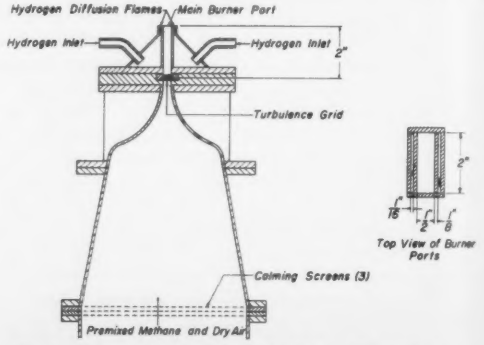

Fig. 1 Schematic drawing of turbulent flame burner

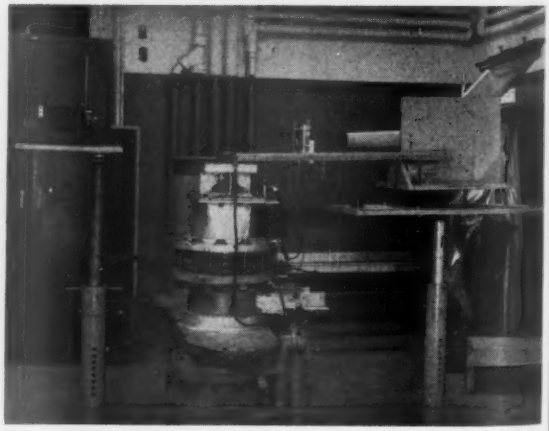

Fig. 2 Turbulent flame burner mounted vertically with Hilger spectrograph at right and camera at left

and the setup of the equipment is shown in Fig. 2. The burner was positioned vertically to avoid asymmetric distortions due to buoyancy of the hot gases. Flow velocities up to 120 ft/sec were attainable at the burner port and, to prevent blow-off, the flames were anchored in the high speed stream by small hydrogen diffusion flames burning on narrow slots along the two sides of the main burner port. The turbulence generating grids were mounted in interchangeable

frames 2 inches below the port. Two grids were employed, in addition to a clear-passage frame: one consisted of $^1/_{16}$-in. round rods located on $^1/_8$-in. centers, with two sets of rods crossing at right angles; the other consisted of $^1/_8$-in. rods on $^1/_4$-in. centers. Turbulence in the flow approaching the grids was damped out by fine-mesh calming screens and an 80-to-1 area ratio contraction section. The turbulence intensity (u'/U) produced by the grids at the port was of the order of 10 per cent, based on turbulence decay correlations of Simmons and Salter (12).

The fuel selected for the experiments was commercial grade methane, which is described as consisting of 93.5 per cent methane plus at least 5 per cent paraffinic hydrocarbon gases. The measured laminar burning velocity was substantially in agreement with published data for pure methane. The air was taken from a 2500-psi general laboratory supply, regulated down to a low pressure level before admission to the burner. Premixing of fuel and air was accomplished in a packed bed flow section upstream of the calming screens. Flow rates of air, methane, and hydrogen were measured by a rotameter and two orifice meters, respectively. The general appearance of the flame, without a grid and with the $^1/_4$-in. mesh grid, is shown in Fig. 3; comparison of the two photographs shows the effect of turbulence in shortening the flame zone, since the flow rates and mixture ratios were the same in each case.

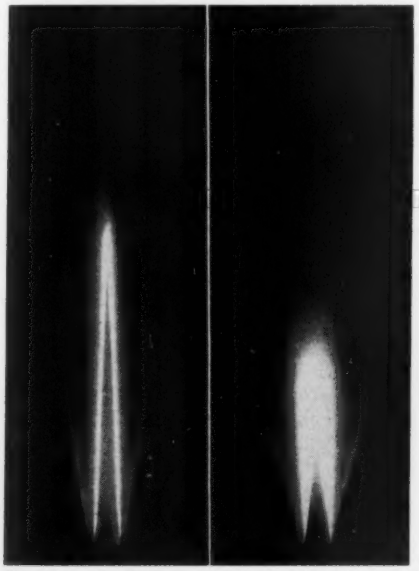

Fig. 3. Methane-air flames with and without turbulence in approach flow. 8% feel/air. Air flow, 70 ft/sec. Turbulence grid $^1/_4$-in. mesh

Filtered Photographs of the Turbulent Flame

The first experiment to test the validity of the fluctuating laminar flame model consisted of making a photographic survey over the entire flame zone of the relative intensity of light emission from the various emitters that normally radiate in a laminar methane-air flame. This was done by photographing the same flame through different interference-type filters, each selected to admit a part of the spectrum at which a particular emitter radiates.

Behind this test was the following reasoning. A laminar flame is very thin at atmospheric pressure, in comparison with a turbulent flame zone, and if laminar flames are present in every region of a turbulent flame, then all the characteristic radiations of a laminar flame should be observable in every region of a turbulent flame. More precisely, if attention is focused on the path of the fuel-air mixture as it flows into the burning zone, the onset of emission by a product molecule such as H_2O should not lag the onset of emission by a transient radical such as CH by more than the thickness of a laminar flame. From results of experiments by Wohl (14), in which the intensities of various emissions were traced with high resolution through a laminar butane-air flame, it can be seen in Fig. 4 that the spatial lag should be expected to be less than $^1/_2$ mm. To confirm Wohl's result for a laminar flame, and to test the proposed experiment, a laminar methane-air flame on a round bunsen burner was photographed with a 4 × 5 Speed Graphic plate camera, first through a 4300 AU filter (CH emission) and then through a 9300 AU filter (H_2O emission). The two photographs are compared in Fig. 5

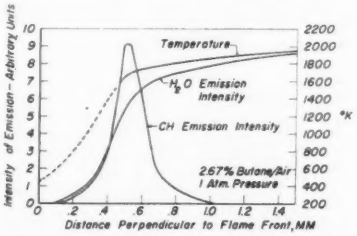

Fig. 4 Distribution of radiation intensity through a 2.67% butane-air laminar flame at 1 atm pressure, at 4315 AU (CH) and 2.505 μ(H_2O)

Temperature distribution deduced from infrared radiation intensity (solid line) and estimated from thermocouple traverses of low pressure flames (dashed line). Data taken from Wohl (14) and Friedman (13).

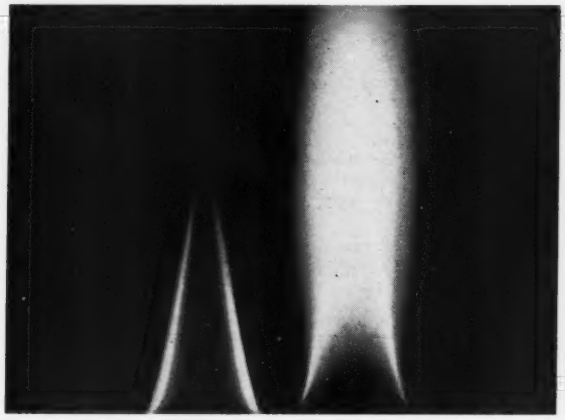

Fig. 5. Laminar flame on tube burner, photographed through 4300 AU filter (CH) and through 9300 AU filter (H_2O). 7.3% fuel/air.

The principal observable difference is that H_2O continues to radiate above the primary flame zone, whereas CH does not radiate anywhere except in this zone. This is not surprising, since H_2O is a permanent product of combustion and radiates as long as it is hot, whereas CH is consumed in the primary flame zone. The important point to notice is that H_2O emission starts very close to the start of CH emission.

The result of the test performed on a turbulent flame is shown in Fig. 6. The same filters, 4300 and 9300 AU, were employed for this pair of photographs. It is evident that the onset of H_2O emission does *not* take place within $^1/_2$ mm of the onset of CH emission, but lags behind it at distances of 2 to 10 mm in various parts of the flame zone. The exposure times were chosen to produce approximately equal maximum densities on the two plates, in order to be sure to avoid any false space lag due to the low intensity of the H_2O radiation. A more accurate comparison of such filtered pictures is shown in Fig. 7, by means of superimposed tracings of the flame boundaries as photographed through the two filters.

Clearly, the results of these experiments are in sharp con-

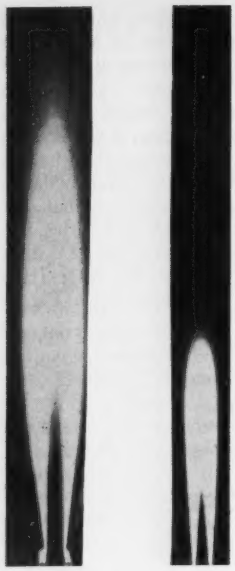

Fig. 6

Turbulent flame photographed through a 9300 AU filter (H_2O) and through a 4300 AU filter (CH). 9.7% methane/air. Air velocity, 70 ft/sec, 1/4-in. mesh grid

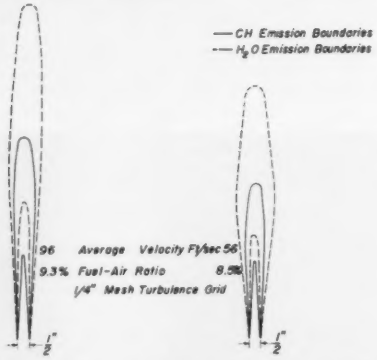

Fig. 7 Outlines of two turbulent flames, each photographed through a 4300 AU filter (CH) and a 9300 AU filter (H_2O)

tradiction with the fluctuating laminar flame model of a turbulent flame. It seems, instead, that the reaction is distributed over a fairly deep zone, ten to a hundred times thicker than the normal laminar flame.

Spectroscopic Traverses of the Turbulent Flame

The distribution of characteristic radiations in the turbulent flame zone was investigated in another way. A Hilger intermediate quartz spectrograph was used to traverse the flame zone along preselected "cuts" as shown in Fig. 8. An image of the flame is focused on the entrance slit of the spectrograph with a quartz lens, the slit thereby admitting a "slice" of the flame. Images of this slice are thus recorded on the spectrum plate in every "color" emitted by the flame. Each spectrum line on the plate therefore represents an intensity traverse in a particular wavelength of the slice of the flame.

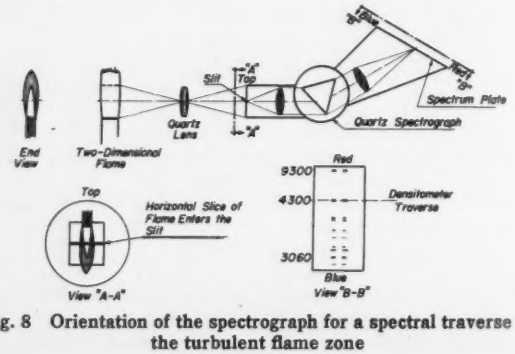

Fig. 8 Orientation of the spectrograph for a spectral traverse of the turbulent flame zone

A print of a typical turbulent flame spectrum is shown in Fig. 9. The scale alongside the spectrum gives the approximate wavelength in units of 100 AU. The most interesting bands for this study are those of OH (3060 AU), CH (4300 AU), and H_2O (9300 AU). The first feature to observe is that the spectrum is divided into two stripes. This follows directly from the fact that the slit straddled the two legs of

Fig. 9 Typical spectrum obtained with spectrograph set up in Fig. 8

Three bands of interest are located at 3060 AU (OH), 4300 AU (CH), and 9300 AU (H_2O). (Wavelength scale photographed on the plate is slightly off.) Fuel/air ratio, 9.6%. Velocity 73 ft/sec; 1/8 inch mesh grid. See References (15) and (16) for band identifications.

the two-dimensional flame, as shown in Fig. 8. The significant result of this investigation is that the H_2O band at 9300 AU has a much broader dark gap in the center than the bands of either CH or OH. This is confirmed quantitatively by comparison of the densitometer traverses of these three bands, as shown in Fig. 10. The vertical scale shows the relative intensity of the transmitted densitometer beam as it traversed the plate of Fig. 9, and the horizontal distance scale has been translated into actual distances in the flame zone.

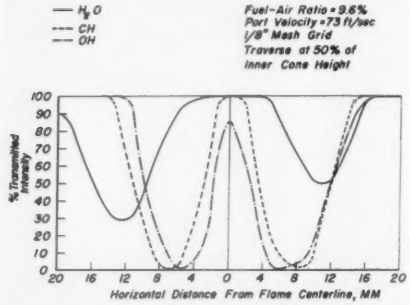

Fig. 10 Comparison of densitometer traverses of spectrum plate of Fig. 9 to bring out the relative positions of the emitters in the flame zone

The results of this spectral analysis confirm the findings of the filtered photographs, namely, that the reactions in the turbulent flame are spread out over a zone much deeper than the thickness of a laminar flame.[7]

Ionization Fluctuations in Turbulent Flames

A third test of the structure of a turbulent flame was modeled after certain experiments by Karlovitz, et al. (22) on fluctuations of the ionic conductance of flames. It is well known that the ion concentration in a laminar flame is several orders of magnitude greater in the immediate vicinity of the active reaction zone than in the hot gas above it. Therefore, if a laminar flame is traversed by a nichrome wire probe connected to a circuit designed to measure the electrical resist-

[7] W. G. Agnew reported similar separations in propane flames for the regions of C_2 (5165 AU) and CH (4317 AU) emissions, not for the onset of the radiation, but for the disappearance of the two radiations near the end of combustion. These results based on tests made in 1949 led him to propose a "zone of reaction" instead of a "flame front" (23).

ance of the flame, the flame will exhibit a high resistance everywhere except in the active reaction zone. If the probe is positioned in a turbulent flame, the measured resistance will fluctuate as the local ionic concentration surrounding the probe fluctuates. The point of the test is this: If the turbulent flame is merely a nonsteady wrinkled laminar flame, then the over-all flame resistance will fluctuate from high levels when the laminar flame is not in contact with the probe to low levels when it is in contact, and intermediate values should be rare; on the other hand, if reaction is taking place throughout the turbulent flame zone, in pockets of varying degrees of reaction distributed at random, then the instantaneous resistance should show a wide range of values corresponding to the random distribution of ion concentration.

The probe circuit, copied from a design supplied by Karlovitz and his colleagues at the Bureau of Mines, is shown in Fig. 11, and the characteristic curve of output voltage signal

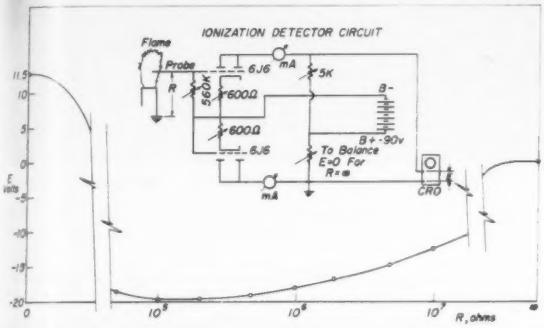

Fig. 11 Flame ionization detector circuit measures instantaneous electrical resistance of the flame between the bare probe and the burner (ground). Characteristic curve shows output signal voltage vs. input resistance

against input flame resistance is shown in the same illustration. For an equivalence ratio of about one, the observed range of flame resistance was of the order of 10^8 ohms, corresponding to a probe output signal of about 1 volt.[8] Leaner flames indicated considerably higher resistance. The response time of the measuring circuit was shorter than 5×10^{-5} sec on the basis of the observable detail in the oscillograms. The time interval required for a laminar flame ionization zone to pass the probe, with a port velocity of 50 ft/sec, would be at least 5×10^{-5} sec, so that the probe circuit was deemed capable of detecting the passage of individual laminar flame sheets even if they were closely packed in the turbulent flame.

The probe itself was an uncoated 0.0055-in. nichrome wire about 2 inches long. It was sufficiently sturdy to withstand the heating and the stream impact, and it was sufficiently thin not to act as a flameholder or to disturb the flame visibly. The output signal produced by the probe as it traversed a Bunsen-type laminar flame is shown in Fig. 12. The effective thickness of a laminar flame is about 1.3 mm at f/a equivalence ratio of 0.97. This agrees with the measurements of Karlovitz (22).

Typical oscillograms for a probe positioned in a turbulent flame are shown in Fig. 13. The points of significance are: (1) that the signal voltage exhibits a broad range of values, with the important intermediate values occurring quite frequently; (2) that the signal voltage never goes to zero, indicating that an appreciable ion concentration is always in

[8] Unfortunately, a calibration of the response of the probe circuit in the range of 10^8 ohms was not made before the equipment was disassembled, but an extrapolation based on analysis of the circuit indicates that a signal of 1 volt corresponds to about 10^8 ohms. In the range of resistance in which the circuit was used, the voltage signal is approximately proportional to the conductance. Of course, the conclusions reached from these tests do not require a precise conversion from voltage signal to flame conductance.

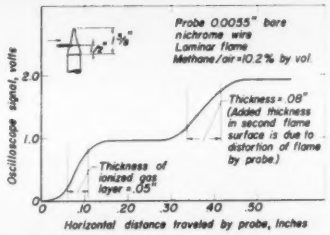
Probe 0.0055" bare nichrome wire
Laminar flame
Methane/air=10.2% by vol.
Thickness = .08"
(Added thickness in second flame surface is due to distortion of flame by probe.)
Thickness of ionized gas layer = .05"
Oscilloscope signal, volts
Horizontal distance traveled by probe, inches

Fig. 12. Ionization probe traverse of a laminar bunsen flame

The straight wire probe penetrated the flame perpendicular to the surface. The conductance of two flame sheets is twice that of one.

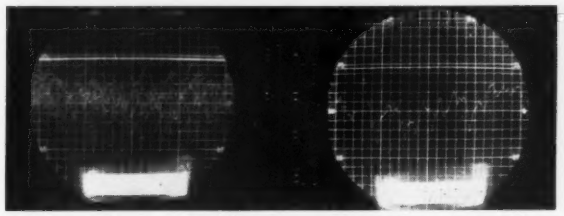

Fig. 13 Cathode ray oscillograms with probe in the middle of the flame zone

Single sweep trace (about 0.006 sec) and continuous sweep (170 cps). Signal voltage is given by magnitude of downward deflection from zero line.

contact with some portion of the probe: (3) that the conductance of the turbulent flame reaches peak values that considerably exceed the conductance of a laminar flame. A summary of the data obtained from similar oscillograms taken at various stations in the flame is provided in Fig. 14. The flame conductance is greater at stations higher up in the brush; this indicates an increase in average ion concentration as combustion proceeds. While oblique or multiple penetrations of a flame sheet might explain the high conductance peaks, the absence of small values is not so easily explained. It seems clear, on the basis of the foregoing argument, that the flame gas that was swept by the probe contained not

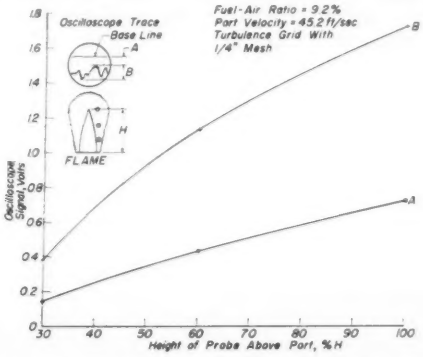

Fig. 14 Ionization probe traverse of turbulent flame showing variation of "minimum signal" and "oscillating signal" amplitudes with vertical position. Electrical conductance increases with height of probe above port

simple laminar flame elements but rather a random distribution of pockets of gas at various stages of reaction and containing various concentrations of ions. The results cannot fit the fluctuating laminar flame description of a turbulent flame.

Temperature Distribution Across a Turbulent Flame

The fourth test concerned with the structure of the turbulent flame deals with the distribution of temperature through the flame zone. A typical traverse made with an

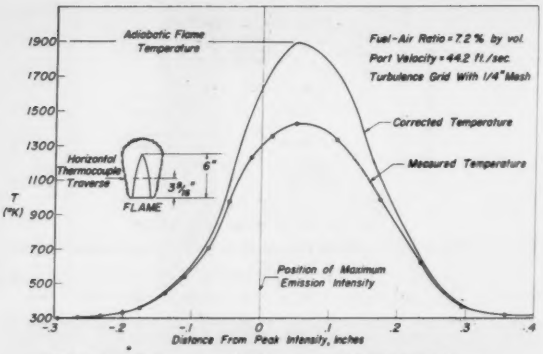

Fig. 15. Thermocouple traverse of turbulent flame

Corrected temperatures are calculated by assuming that the true gas temperature at the peak is the adiabatic flame temperature and that error is due entirely to radiation from the thermocouple.

alumel-chromel thermocouple is shown in Fig. 15. The wire was No. 28 B&S gage, butt welded to form a 0.038-in. bead. There was no observable disturbance of the flame in the vicinity of the junction. Only lean mixture flames were tested in this manner, to keep within the temperature limitations of the thermocouple metals. Chromel-alumel was chosen for the thermocouple because previous work by Wright and Becker (17) had shown that hydrocarbon-air flames are not disturbed catalytically by these materials.

The corrections for radiation error were made by means of the following formula

$$T_{gas} = T_{wire} + aT_{wire}^4 \quad \ldots\ldots\ldots\ldots\ldots\ldots [5]$$

The parameter a includes the convective heat transfer coefficient, the emissivity of the bead, and the dimensions of the bead. It was assumed that, for any particular traverse, a would be nearly constant, and that it could be evaluated by equating the error at the peak of the curve to the difference between the adiabatic flame temperature and the observed temperature. The remainder of the curve was corrected with the same value of a.

The temperature distribution was located as precisely as possible with reference to the peak of the emission contour. This was done by photographing the flame with the thermocouple in place, and noting the indicated temperature. The plate was then scanned with a microdensitometer to provide the couple location on the density contour.

It can be seen from Fig. 15 that the peak CH emission (4300 AU) occurs at a place where the temperature has already risen about 85 per cent of the way from initial to peak value. If a turbulent flame were really a fluctuating laminar flame which spends half the time on one side of its most probable position and half the time on the other side, then the temperature profile should show only 50 per cent of the temperature rise at this position because this would be the place where half the fuel would be burned. The observed rise is 85 per cent, not 50 per cent, which indicates a similarity with the behavior of a laminar-type flame zone as shown in Fig. 4. It seems, therefore, that a turbulent flame is not simply a fluctuating laminar flame but really a deep zone of distributed reaction with light emission being strongest on the hot side of the flame.

Spark Shadowgraph of a Turbulent Flame

In most of the tests the effective turbulent flame velocity was less than six times the normal burning velocity of the laminar flame. According to the wrinkled flame model, the area increases due to turbulent motion should be no more than 6-fold. If this model is correct, a short-duration (20 microsec) spark shadowgraph should be able to resolve the wrinkled flame surface fairly well because of the relatively moderate degree of distortion. The pictures that we have taken indicate instead a highly granular flame zone, with many irregularities as small as 1 mm and possibly even smaller. Fig. 16 is a typical photograph at approximately one-to-one scale. Notwithstanding the difficulty of differentiating between composition inhomogeneities and temperature inhomogeneities, and despite the granulation that must occur by superposition of many irregularities within the flame along the line of sight, it is unlikely that these pictures represent merely a moderately wrinkled laminar flame or that flame fronts can be detected positively at all. It is equally possible that the irregularities visible in the pictures are the result simply of the statistical fluctuations of temperature and composition.

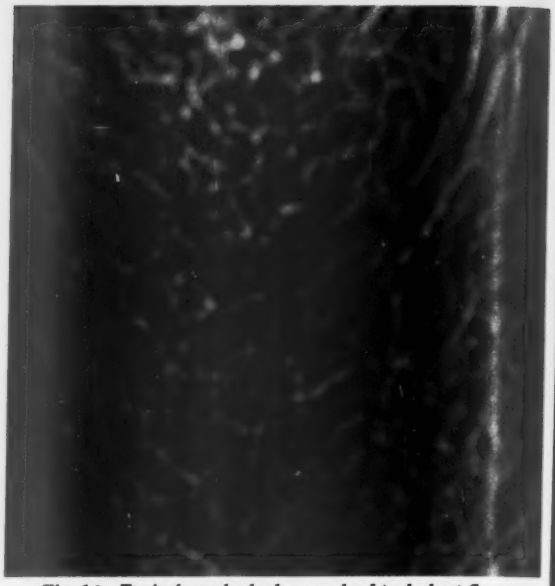

Fig. 16 Typical spark shadowgraph of turbulent flame

Exposure time, about 20 microsec. Velocity, 44 ft/sec. 7.2% fuel/air.

A Theory of Turbulent Flame Propagation

On the basis of the results of these experiments on the internal physical structure of turbulent flames, it seems reasonable that a turbulent reaction zone propagates in principle like a laminar reaction zone, and that a theory for turbulent flame propagation can be constructed along the lines of the existing theory for laminar flame propagation. In constructing this theory, we have adopted an earlier approach of von Kármán and Marble (11). It should be noted that the particular approach described here differs sharply from most previous theories in that it rejects the notion that the active agent inside the turbulent flame is a normal laminar flame. The theory of the homogeneous stirred reactor developed by Avery and Longwell (21) also rejects the normal laminar flame as the active agent. However, their theory may be regarded as the extreme limit of the model employed here, since it presupposes such complete turbulent mixing as to make the composition and temperature uniform throughout the combustion zone.

The complete theory of the laminar flame is known to involve heat conduction, diffusion of all components in the mixture, and the kinetics of all reaction steps involved in the over-all reaction. An accurate theory of this kind for the turbulent hydrocarbon flame does not seem possible at this time without more detailed knowledge of hydrocarbon com-

bustion. But, just as in the case of the laminar flame (18), useful results can be obtained by applying a purely thermal theory in which the reaction is treated as a one-step process.

The temperature distribution in a steady one-dimensional flame zone (18) can be described by the following differential equation

$$\left(\frac{\lambda\rho}{m^2c_p}\right)\left(\frac{de}{dt}\right)\left(\frac{d\theta}{de}\right) = \theta - e \quad \ldots\ldots\ldots\ldots [6]$$

A solution of this equation, with the usual boundary conditions, exists for only one value of the mass flow m, hence for a particular flame speed.

The same formal equation can be written for either the laminar or the turbulent case. In the latter case, λ would be replaced by $\rho c_p \epsilon$, where ϵ is the turbulent diffusivity. Then, three plausible assumptions are introduced in the turbulent flame case:

(a) The growth of ϵ from the cold to the hot side follows the same dependence on temperature as $\lambda/\rho c_p$.

(b) The local reaction rate under turbulent conditions is proportional to the local reaction rate under laminar conditions for the same values of θ and e, and the proportionality constant is the inverse ratio of the respective mean reaction times. The mean reaction time is $d\rho/m$, where d is the observed flame thickness. (If the time lag between the onset of CH and H_2O radiation is used as a measure of the chemical reaction time, then it seems that the turbulent reaction rate is not greatly different from the laminar rate. In both cases, the time lag is about $^1/_4$ millisec.)

(c) The boundary conditions for temperature and reaction rate at the cold and hot sides of the zone are the same for laminar and turbulent flames of the same composition.

When the turbulent flame differential equation is compared with the laminar equation, the existence of a unique turbulent flame speed can occur only if

$$\frac{m_T d_T}{\epsilon\rho} = \frac{m_L d_L}{\nu\rho} \quad \ldots\ldots\ldots\ldots [7]$$

The values of ϵ, ν, ρ are those in the nonburning approach flow. Introducing the burning velocity S, Equation [7] becomes

$$\frac{S_T d_T}{\epsilon} = \frac{S_L d_L}{\nu} \quad \ldots\ldots\ldots\ldots [8]$$

Each side is a dimensionless number of the character of a Reynolds number. We have referred to this equation as a "similarity hypothesis," which is to be tested by experiment.

Test of Similarity Hypothesis for Flame Speed

To test the validity of Equation [8] it was decided to measure turbulent flame speed S_T and flame thickness d_T under various conditions of turbulence ϵ and with various fuel-air ratios. Inasmuch as laminar flame thickness data are not available, the experiments were confined to testing the statement

$$\frac{S_T d_T}{\epsilon} = \text{function of fuel-air ratio } \textit{only} \quad \ldots\ldots [9]$$

Fifteen flame tests were carried out and are reported herein. Flame speed was determined by dividing the volume flow by the effective surface area of the flame. The surface area was determined by tracing the contour of maximum photographic density, as described by Fig. 17. Flame thickness was determined in a somewhat arbitrary fashion, by multiplying the spreading angle of one leg of the flame, by the height of the peak density contour on the flame axis. All the tests are shown in Figs. 18 and 19.

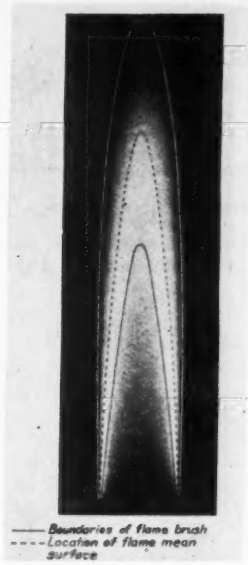

Fig. 17 Scheme for determining effective burning surface area, thereby effective turbulent flame speed

Center line of flame is the peak photographic density contour. Diagram taken from Bollinger and Williams (7).

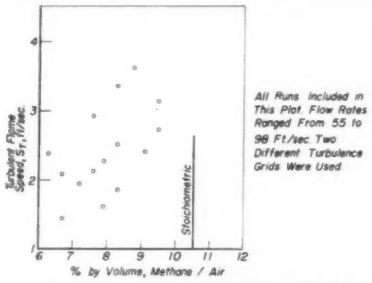

Fig. 18 Turbulent flame speed plotted against fuel-air ratio

All runs are included: Air velocities, 55 ft/sec to 98 ft/sec. Fuel-air ratios, 6.3 to 9.5%. Grid meshes, $^1/_4$ inch and $^1/_8$ inch.

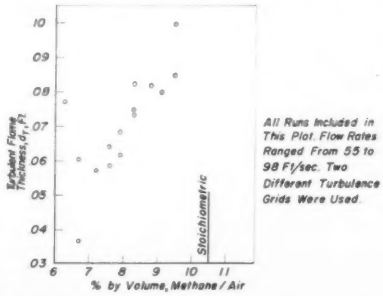

Fig. 19 Turbulent flame thickness plotted against fuel-air ratio

All runs included, as in Fig. 18.

The two previously mentioned turbulence grids were used to create approach turbulence. The turbulence characteristics were not measured. Instead, published correlations (12, 19) were used to estimate the intensity and the scale.

The turbulent diffusivity was evaluated from the Prandtl relation

$$\epsilon = v'l \quad \ldots\ldots\ldots\ldots [10]$$

Published decay data indicate that (for fixed distance)

$$v' \sim UM^{1/2} \qquad (M \text{ is mesh size}) \quad \ldots\ldots [11]$$

$$L \sim M^{1/2} \quad [12]$$

$$\lambda \sim U^{-1/2} \quad [13]$$

It is possible to identify the mixing length l with either the integrated scale L or the microscale λ. Therefore, two possible relations were tested

$$\text{Macroscale assumption:} \quad \epsilon \sim MU \quad [14]$$

$$\text{Microscale assumption:} \quad \epsilon \sim \sqrt{MU} \quad [15]$$

According to these two possibilities, the experimental results are plotted in Figs. 20 and 21. Although it may seem

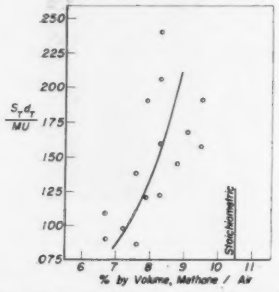

Fig. 20 Test of similarity hypothesis for correlating turbulent flame speed

Integrated scale multiplied by cross-stream turbulent velocity component is identified as turbulent diffusivity. All runs included, as in Fig. 18.

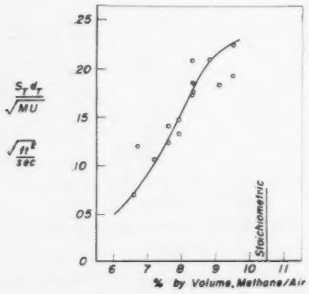

Fig. 21 Test of similarity hypothesis for correlating turbulent flame speed

Microscale multiplied by cross-stream turbulent velocity component is identified as turbulent diffusivity. All runs included, as in Fig. 18.

that the microscale assumption is the preferable one,[9] the choice is not clear-cut in view of the uncertainties involved in evaluating S_T, d_T, and ϵ.

A more convincing test of the validity of Equation [8] is to evaluate each side numerically. Using the best available data for turbulent intensity and scale, the left side of the equation, for the tests near the stoichiometric ratio, comes out to be 6.5 for the macroscale assumption and 16 for the microscale assumption. The right side of the equation can be evaluated using laminar flame thickness data reported by Dixon-Lewis (20). It comes out to be about 10. The fair agreement is significant when it is considered that the individual numbers for the transport coefficients and the flame thicknesses that enter into the two sides of Equation [8] differ by factors up to 100.

[9] It is of interest that the shape of the experimental curve of Fig. 21 can be predicted approximately by evaluating the right member of Equation [8] by means of the well-known Mallard-Le Chatelier formula for flame speed. Other more exact theories would predict a similar shape.

Conclusion

On the basis of the preceding evidence concerning the physical structure of intense turbulent flames and the fair success in correlating the observed turbulent flame speeds by a theory based on reaction in depth, it appears that the wrinkled laminar flame description of turbulent flames should be abandoned in favor of a distributed reaction zone model. In this direction lies the possibility of predicting on a rational basis the length of a ramjet combustion chamber needed for the completion of combustion, an objective of great practical importance.

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Optimum Climbing Technique for a Rocket-Powered Aircraft

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This paper contains a preliminary investigation of the flight path which minimizes both the time and the propellant expenditure necessary to fly a rocket-powered aircraft from a given combination of speed and altitude to another combination of speed and altitude.

Nomenclature

A_e = exit area of the rocket, ft^2
C_D = drag coefficient
C_{D0} = drag coefficient at zero lift
D = drag, lb
D_0 = zero-lift drag, lb
e = aircraft efficiency factor
g = acceleration of gravity, ft sec^{-2}
h = altitude, ft
h_e = $h + V^2/2g$ = energy height, ft
L = lift, lb
m = instantaneous mass of the aircraft, lb ft^{-1} sec^2
m_p = mass of propellant consumed per unit time, lb ft^{-1} sec
M = Mach number
p = atmospheric pressure, lb ft^{-2}
p_e = static pressure in the exit section of the nozzle, lb ft^{-2}
p_L = local static pressure at a point of the external walls of the aircraft, lb ft^{-2}
R = air constant, ft^2 sec^{-2} °R^{-1}
R_e = Reynolds' number
S = wing surface, ft^2
t = time, sec
T = thrust, lb
V = absolute velocity of the aircraft, ft sec^{-1}
W = weight of the aircraft, lb
W_e = average value of the axial component of the relative velocity of the gases in the exit section of the rocket; i.e., velocity referred to a reference frame rigidly connected to the solid part of the aircraft, ft sec^{-1}
$\dot{w}_f$ = weight of fuel consumed per unit time for an aircraft equipped with air-breathing engines, lb sec^{-1}
α = derivative of the air temperature with respect to altitude, °R ft^{-1}
γ = ratio of specific heat at constant pressure to specific heat at constant volume = 1.4 for air
ε = specific energy, ft^2 sec^{-2}
θ = inclination of the flight path with respect to a horizontal plane (positive for climbing flight)
Λ = aspect ratio
ρ = air density, lb sec^2 ft^{-4}

Subscripts

1 = initial condition (time instant t_1)
2 = final condition (time instant t_2)
0 = either a condition at time instant $t = 0$ or a zero-lift condition
inc. = incompressible flow condition
SL = sea level condition

Superscripts

′ = derivative with respect to altitude

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Introduction

CONSIDERABLE attention has been devoted in recent years to the study of the optimum paths of nonsteady flight for high-speed airplanes. Typical problems investigated are the following: the climbing flight of minimum time (1–4, 6–8);[2] the climbing flight of minimum fuel consumption (1, 4, 7, 8); the steepest climb (4, 8). For the particular case of turbo-jet aircraft a systematic application of the theory was developed in (5) and (9).

Because of the analytical difficultics associated with the problem, early investigations were based on several assumptions concerning the equations of the motion, in particular: (a) the mass of the aircraft is a constant; (b) the equation of motion along the normal to the flight path is approximated with $L = W$. These two hypotheses, equivalent to assuming a drag function of the type form $D = D(V, h)$, lead to a simplified form of the minimal problem, which was solved in (1, 2, 4).

In (1) it was shown that the problem of transferring a constant mass aircraft from a velocity V_1 and altitude h_1 to a velocity V_2 and altitude h_2 with the minimum time or with the minimum fuel consumption or with the minimum space flown horizontally, is generally solved by a special path composed of three ares: (a) an initial vertical arc starting at 1; (b) a final vertical arc arriving at 2; (c) a connecting central pattern of equation

$$\left[\frac{\partial F}{\partial V}\right]_h - \frac{V}{g}\left[\frac{\partial F}{\partial h}\right]_V = 0 \qquad [1]$$

where $F = (T - D)V$ for the minimum time problem, $F = (T - D)V/\dot{w}_f$ for the minimum fuel consumption problem and $F = T - D$ for the steepest climb.

For the case of a rocket-powered aircraft the afore-mentioned minimal problems are complicated by the necessity of accounting for the variation of mass with time. No published investigation is known to the writer except an early attempt by Lippisch (10), whose Eulerian solution refers to the class of all possible flight paths satisfying the condition $C_D = \text{const.}$

Lippisch's solution, however, is incomplete in so far as the boundary conditions are not satisfied, both for the free boundary-value problem to which this author refers (V_1, V_2 free) and for the fixed-end points problem (V_1, V_2 given). It is to be noted that Lippisch became aware of the *non-extremal character* of his solution through a numerical example consisting of the comparison of the Eulerian trajectory with two arbitrary paths of flight, one in which the dynamic pressure is constant and one in which the velocity of flight is constant.

Object of the Present Research

The scope of the present work is to determine the climbing technique for minimum time of a rocket-powered aircraft; i.e., the speed-height relationship $V = V(h)$ which minimizes the time necessary to fly from a given initial condition (h_1,

[2] Numbers in parentheses indicate References at end of paper.

V_1) to a given final condition (h_2, V_2). The main idea is to reduce the mathematical form of the minimal problem to the model already solved for a constant mass aircraft, by introducing convenient engineering assumptions into the equations of the motion.

Fundamental Equations

The following hypotheses are used throughout the paper: (A) the rocket-powered aircraft is ideally regarded as a particle of variable mass; (B) only flight paths contained in a vertical plane are considered; (C) the small angle between thrust vector and velocity vector is neglected; (D) the motion of the propellant in the piping system, in the combustion chamber, and in the nozzle is steady with respect to a reference frame rigidly connected to the solid part of the aircraft; (E) the aerodynamic lag is disregarded; i.e., lift and drag forces are calculated as in steady flight.

Because of the assumptions (A), (B), and (C) the equations of the motion along the tangent and along the normal to the flight path are written as follows (1, 11, 12):

$$T - D - m\,(g + VV')\sin\theta = 0 \qquad [2]$$

$$L - m\,(g\cos\theta + V^2\theta'\sin\theta) = 0 \qquad [3]$$

As a consequence of the hypotheses (D), the mass of the aircraft is a linear function of the time

$$m = m_0 - t\sum \dot{m}_p \qquad [4]$$

where m_0 is the mass at the time instant $t = 0$ (arbitrarily chosen) and the summation $\sum$ is extended to all the nozzles of the aircraft in the general case of an airplane equipped with several rocket engines.

For the case of parallel nozzles,[3] the thrust vector[4] is defined as

$$T = \sum (\dot{m}_p W_e + P_e A_e) - p\sum A_e \qquad [5]$$

From Equations [2] and [4] and from the definition of rate of climb, the time interval necessary to fly from an initial altitude h_1 to a final altitude h_2 is obtained

$$\Delta t = \int_{h_1}^{h_2} \frac{dh}{V\sin\theta} = \frac{m_1}{\sum \dot{m}_p}\left\{1 - \exp\left(-I\sum \dot{m}_p\right)\right\} \qquad [6]$$

where

$$I = \int_{h_1}^{h_2} (\Phi V' + \Psi)\,dh \qquad [7]$$

$$\Phi = \frac{1}{T - D} \qquad [8]$$

$$\Psi = \frac{g}{V(T - D)} \qquad [9]$$

It is to be noted that for given values of m_1 and $\sum \dot{m}_p$ the time interval Δt is a monotonically increasing function of the integral I (see Equation [6]). As a consequence, the problem of minimizing Δt is essentially identical with the problem of minimizing the integral [7].

In Equations [8] and [9] the variables T and g depend on the altitude only. The drag D is a function of the form $D = D\,(h, V, L)$ because of the hypothesis (E). In addition, the lift is a function of the type $L = L(h, V, \theta, \theta', t)$ because of Equation [3]. As a consequence the two functions Φ and Ψ have in general the form: $\Phi = \Phi\,(h, V, \theta, \theta', t)$, and $\Psi = \Psi\,(h, V, \theta, \theta', t)$.

Solution of the Minimal Problem

The analysis of the minimal problem is difficult in general, since the integral [7] depends on the three functions $V(h)$, $\theta(h)$, and $t(h)$. It is therefore convenient to simplify the equations of the motion by stipulating that the so-called "induced drag" is negligible with respect to the zero-lift drag of the aircraft. The reason for this assumption lies in the fact that, particularly at low altitudes, relatively low angles of attack are used by rocket-powered aircraft in the climbing flight. Mathematically speaking, this hypothesis is equivalent to replacing Equation [3] with the following equation

$$D \cong D_0 = {}^1/_2 C_{D0}\,\rho\,SV^2 \qquad [10]$$

For a given aircraft the drag coefficient at zero lift C_{D0} is a function of the Mach and Reynolds number. For standard atmosphere it is $M = M(V, h)$, $R_e = R_e(V, h)$ and therefore $C_{D0} = C_{D0}\,(V, h)$. The drag of the aircraft is consequently reduced to a function of velocity and altitude only, and the expressions [8] and [9] simplify to $\Phi = \Phi\,(V, h)$, $\Psi = \Psi\,(V, h)$. It follows that the integral [7] to be minimized takes the form

$$I = \int_{h_1}^{h_2} \left\{\Phi(V, h)V' + \Psi\,(V, h)\right\} dh \qquad [11]$$

and is therefore reduced to the well-known type already treated in (1, 2, 4) for a constant mass aircraft.

Due to the mathematical analogy existing between the actual simplified minimal problem and the form of the problem (1, 2, 4), the general demonstration is here omitted and the reader is referred to the bibliography.[5] Only the results

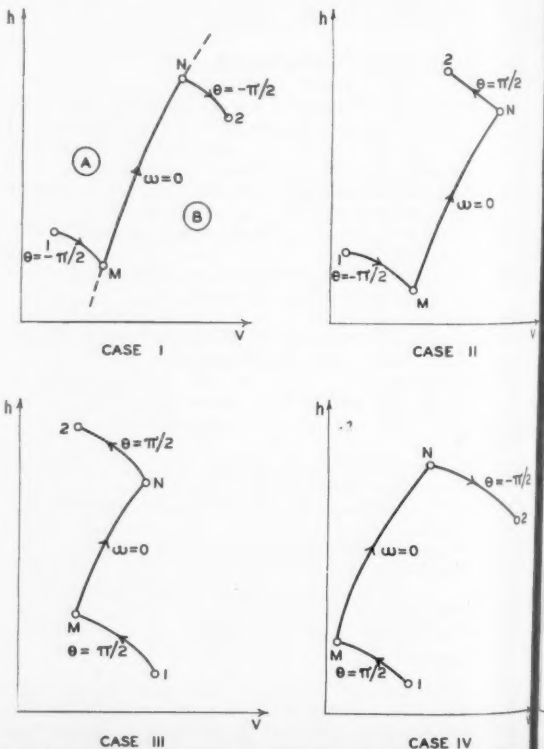

Fig. 1 Optimum speed-height relationships for the general ca

[3] In the following discussion the subscript i denoting magnitudes relative to the particular nozzles is omitted for simplicity. Thus $\dot{m}_{pi}$, W_{ei}, p_{ei}, A_{ei} will be written as $\dot{m}_p$, W_e, p_e, A_e, respectively.

[4] As a consequence of the definition [5] for the thrust, the resultant aerodynamic force *must* be considered as the integral of all tangential actions and of normal actions due to the pressure difference $p_L - p$ (p_L = local static pressure). Such an integral is extended to all the external areas of the aircraft, *excluding* the exit area A_e of the nozzle.

[5] For the particular case $h_1 \leq h \leq h_2$, a proof of the minimal character of the path $1MN2$ is outlined in Appendix A.

Table 1 Optimum speed-height relationships

Case of flight	Region where point 1 belongs	Region where point 2 belongs	Arc $1M$	Arc MN	Arc N_2	Remarks
I	A	B	$\theta = -\pi/2$	$\omega = 0$	$\theta = -\pi/2$	No limitations imposed on the flight path
II	A	A	$\theta = -\pi/2$	$\omega = 0$	$\theta = +\pi/2$	
III	B	A	$\theta = +\pi/2$	$\omega = 0$	$\theta = +\pi/2$	
IV	B	B	$\theta = +\pi/2$	$\omega = 0$	$\theta = -\pi/2$	
I	A	B	$h = h_1$	$\omega = 0$	$\theta = -\pi/2$	$h \geq h_1$
II	A	A	$h = h_1$	$\omega = 0$	$\theta = +\pi/2$	
III	B	A	$\theta = +\pi/2$	$\omega = 0$	$\theta = +\pi/2$	
IV	B	B	$\theta = +\pi/2$	$\omega = 0$	$\theta = -\pi/2$	
I	A	B	$h = h_1$	$\omega = 0$	$h = h_2$	$h \geq h_1$ $h \leq h_2$
II	A	A	$h = h_1$	$\omega = 0$	$\theta = +\pi/2$	
III	B	A	$\theta = +\pi/2$	$\omega = 0$	$\theta = +\pi/2$	
IV	B	B	$\theta = +\pi/2$	$\omega = 0$	$h = h_2$	

are given, with some extension.

The speed-height relationship $V = V(h)$ which minimizes the integral [11] and satisfies the boundary conditions (h_1, V_1), (h_2, V_2) is composed of three arcs:

(A) A central arc defined by an equation independent of the boundary conditions of the problem

$$\omega(V, h) = \left[\frac{\partial \Psi}{\partial V}\right]_h - \left[\frac{\partial \Phi}{\partial h}\right]_V = 0 \quad \ldots\ldots\ldots [12]$$

(B) An initial arc $1M$ and a final arc $N2$ which depend on the boundary conditions of the problem (Refs. 1, 4).

Four types of boundary conditions are possible according to the relative position of points 1 and 2 with respect to the curve $\omega = 0$ (Ref. 1). Four different solutions are accordingly found for the terminal branches $1M$ and $N2$. These solutions are indicated in Table 1 and Fig. 1, where A $(\omega < 0)$ denotes the region of the (V, h)-plane located at the left of the curve $\omega = 0$, and B $(\omega > 0)$ denotes the region at the right of the same curve.

In addition to problems of absolute optimum, problems of conditioned optimum may be handled with the method of (1, 4). Table 1 and Figs. 2 and 3 supply the solution of the minimum time problem under the limitations $h \geq h_1$ and $h_1 \leq h \leq h_2$. The first limitation is of interest in cases where the altitude h_1 is the ground level and means that the aircraft is forbidden to go to altitudes below the initial one. The second limitation means that the search of the optimum flight conditions is limited to the category of paths internal to the region of space bound by the horizontal planes corresponding to the terminal altitudes.

With a transformation of coordinates from the (V, h)-plane

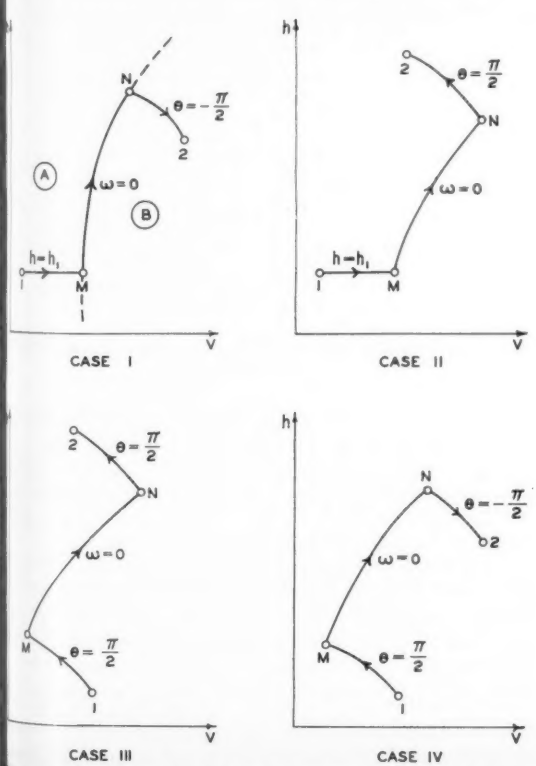

Fig. 2 Optimum speed-height relationships for the case $h \geq h_1$

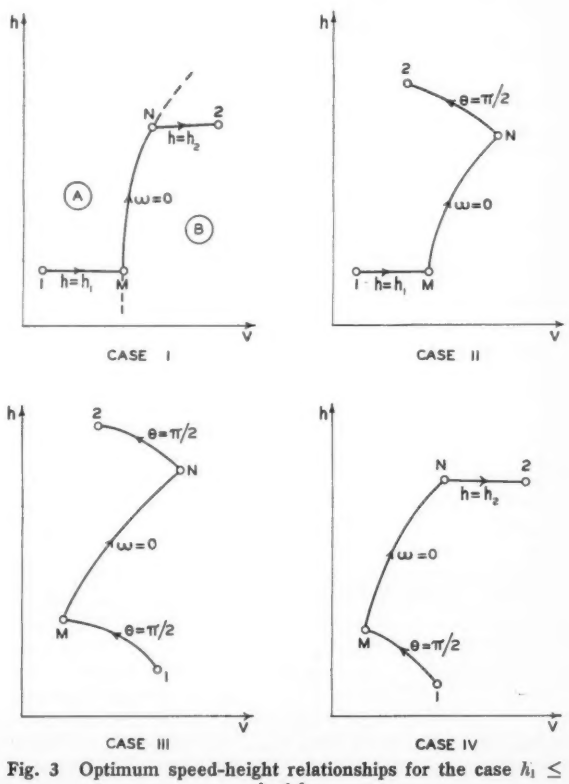

Fig. 3 Optimum speed-height relationships for the case $h_1 \leq h \leq h_2$

to the (V, ϵ)-plane, Equation [12] may be shown equivalent to

$$\left[\frac{\partial(\Psi/g)}{\partial V}\right]_{\epsilon} = 0 \quad \ldots\ldots [13]$$

where

$$\epsilon = \frac{V^2}{2} + \int_{h_{SL}}^{h} g\, dh \quad \ldots\ldots [14]$$

For the particular case g = const, Equation [13] may be rewritten as

$$\left[\frac{\partial \Psi}{\partial V}\right]_{h_e} = 0 \quad \ldots\ldots [15]$$

where $h_e = h + (V^2/2g)$ is the so-called energy height (Ref. 2). The variable ϵ may be designated as *specific energy*. It has the dimensions of an energy per unit mass and is of interest in problems where the acceleration of gravity is considered a function of the altitude.

Optimum Mach Numbers

The central part MN of the optimum distribution of speeds is independent of the boundary conditions and is defined by the equivalent expressions [12] or [13]. From Equations [8], [9], [10], [12], one obtains the following formula for the best speed-height relationship

$$\left[\frac{\partial(TV - D_0V)}{\partial V}\right]_h - \frac{V^2}{g}\left[\frac{\partial(T - D_0)}{\partial h}\right]_V = 0 \quad \ldots [16]$$

Equation [16] may be arranged into a convenient form for applications by neglecting the dependence of C_{D0} on the Reynolds number, by using Equations [5] and [10], the expression of the sonic speed, the derivatives of the density, pressure and temperature of the air with respect to the altitude and by introducing the Mach number in place of the velocity as a variable. The following result is obtained

$$\frac{T}{pS} = \gamma M^2\left[\frac{3}{2}C_{D0} + \frac{M}{2}\frac{\partial C_{D0}}{\partial M} + \frac{\sum A_e}{S}\right] + \frac{\gamma^2 M^4}{2}\left[mC_{D0} + \frac{m-1}{2}M\frac{\partial C_{D0}}{\partial M}\right] \quad \ldots [17]$$

where

$$m = 1 + \frac{\alpha R}{g} \quad \ldots\ldots [18]$$

In general, Equation [17] is to be solved graphically. An analytical solution is possible only in special cases. For instance, if the derivative of the minimum drag coefficient with respect to the Mach number may be neglected, Equation [18] reduces to a biquadratic one, whose solution is the following

$$M = \sqrt{\frac{K}{\gamma m}\left\{-1 + \sqrt{1 + \frac{2m}{K^2}\frac{T}{C_{D0}pS}}\right\}} \quad \ldots\ldots [19]$$

where

$$K = \frac{3}{2} + \frac{\sum A_e}{C_{D0}S} \quad \ldots\ldots [20]$$

Equation [19] may be of use at low altitudes, when the speed for optimum climb still belongs to the region of quasi-incompressible flow. A numerical analysis, however, indicates that the state of flight predicted with Equation [19] at various altitudes is to a first approximation characterized by the constancy of the dynamic pressure. As the altitude increases, both the velocity and the Mach number increase with such rapidity that the hypothesis $(\partial C_{D0}/\partial M) = 0$ is soon no longer satisfied and the calculation of the optimum distribution of speeds is to be carried out with Equation [17].

It is of interest to compare the central part MN of the actual solution with the well-known "quasi-steady" solution of the problem of the best climbing performance. In the quasi-uniform approach the optimum distribution of speeds is defined by

$$\left[\frac{\partial}{\partial V}(TV - DV)\right]_h = 0 \quad \ldots\ldots [21]$$

At low altitudes the hypothesis $D = D_0$ may be introduced in Equation [21], yielding

$$\frac{\partial}{\partial V}\left[(TV - D_0V)\right]_h = 0 \quad \ldots\ldots [22]$$

From Equations [22], [5], [10] and from the definition of Mach number, one obtains the following expressions for the quasi-steady optimum speed-height relationship

$$\frac{T}{pS} = \frac{\gamma M^2}{2}\left[3\,C_{D0} + M\frac{\partial C_{D0}}{\partial M}\right] \quad \ldots\ldots [23]$$

Terms containing $(\partial C_{D0}/\partial R_e)$ have been neglected in Equation [23]. The Mach number solving Equation [23] is designated by M_u. In particular, when the hypothesis $(\partial C_{D0}/\partial M) = 0$ is justified, M_u is given by

$$M_u = \sqrt{\frac{2}{3\gamma}\frac{T}{C_{D0}\,pS}} \quad \ldots\ldots [24]$$

In Fig. 4 the ratio M/M_u between the Mach number M defined by Equation [19] and the Mach number M_u defined by

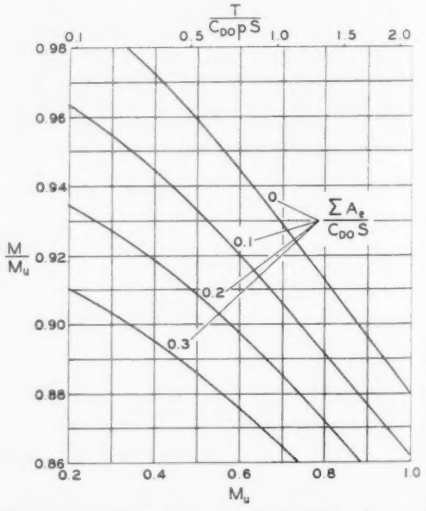

Fig. 4 Optimum velocity for tropospheric flight, incompressible airstream

Equation [24] has been plotted as a function of the parameters $(T/C_{D0}pS)$, $(\sum A_e/C_{D0}S)$ for the incompressible flow case, tropospheric flight. The best climbing technique calculated accounting for the nonsteadiness of the motion is characterized by velocities which are less (2–10%) than the velocities determined with the old quasi-steady treatment.

Fig. 5 shows the results of a typical calculation carried out for a rocket powered aircraft having the following characteristics:

λ = 5	m_1 = 410 lb sec^2 ft^{-1}	T_{SL} = 4410 lb
$(e)_{inc.}$ = 0.8	S = 269 sq ft	$\sum A_e$ = 0.48 sq ft
	$(C_{D0})_{inc.}$ = 0.018	$\sum \dot{m}_p$ = 0.67 lb sec ft^{-1}

The prediction of the drag variation in compressible airstream has been carried out using the data of (13, chapter 2). Three distributions of speed are shown in Fig. 5.

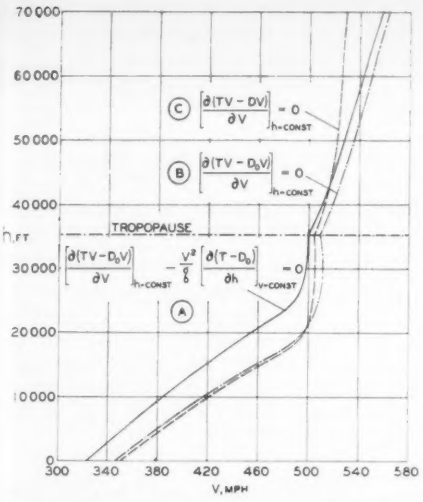

Fig. 5 Comparison between various distributions of speed

1 Distribution A, defined by Equation [16], which accounts for tangential acceleration effects, but neglects the induced drag.

2 Distribution B, defined by Equation [22], which neglects both tangential acceleration terms and induced drag terms.

3 Distribution C, defined by Equation [21] which neglects acceleration terms, but accounts for the "induced drag," by computing the lift according to $L = mg \cos \theta$. In the particular example carried out, the hypothesis [10] concerning the drag of the aircraft is approximately satisfied up to altitudes of about 40,000 ft. Equation [16] predicts the best distribution of speeds $V = V(h)$ with a precision of 2 per cent up to 40,000 ft. At higher altitudes due to the lower air density and to compressibility effects on the drag, the lift coefficient for best climb increases in such a way that the so-called "induced drag" is no longer negligible with respect to the minimum drag.

Remarks

(A) Equation [6] is general and contains the one commonly used in the mechanics of flight of airplanes propelled by air-breathing engines as a particular case. For an aircraft having an ideally constant mass ($\sum \dot{m}_p \to 0$), Equation [6] reduces to

$$\Delta t = m_1 I \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots [25]$$

(B) For a rocket-powered aircraft utilizing constant conditions in the combustion chamber, $\sum \dot{m}_p$ is a constant and the propellant consumption is proportional to the flying time. As a consequence, the path of minimum time is identical to the path of minimum propellant consumption. Such an identity is not verified for aircraft powered by air-breathing engines. For instance, the paths of minimum time and of minimum fuel consumption for a turbojet aircraft differ in so far as the former is to be flown at comparatively higher velocities (4).

(C) The speed-height relationship $V = V(h)$ determined with the present analysis (which accounts for inertia terms) and the distribution of speeds obtained with the old quasi-steady treatment (which neglects inertia terms) differ in so far as somewhat lower velocities are now predicted. For turbojet aircraft, on the contrary, to account for acceleration terms shifts the predicted distribution of speeds toward the region of higher velocities (4).

(D) Of particular importance is the assumption [10] concerning the drag. A verification of such a hypothesis shows that it introduces a relatively small error at low altitudes for the portion MN of the optimum path. As the altitude increases, however, the accuracy in the determination of the best speed-height relationship decreases. Due to the lack of a general analytical relationship between C_D, C_L, and M, it is difficult to define the exact range of applicability of the present theory. It is felt, however, that at higher altitudes the precision of Equation [16] may be improved by substituting in it D in place of D_0.

(E) A numerical example has been carried out for the conditions $V_1 = 300$ mph, $h_1 = 0$ ft, $V_2 = 580$ mph, $h_2 = 50{,}000$ ft, $h_1 \leq h \leq h_2$. The time Δt has been calculated for the three distributions of speed A, B, C of Fig. 5 according to Equations [6], [7], [8], and [9] and assuming $D = D_0$ for the three cases. The results confirm the extremal nature of the optimal solution A.

(F) The optimum speed-height relationship $V = V(h)$ has a corner at the points M and N where the curve $\omega = 0$ intersects the two vertical paths starting at 1 and arriving at 2 (Fig. 1). Such a discontinuity is the consequence of the hypothesis $D = D_0$ and would certainly not exist, should the minimal problem be treated with the exact equations of the motion.

(G) The main advantage of the present solution is centered in its simplicity and ease of computation. Results, of course, must be handled with caution, i.e., taken *cum grano salis* according to the Latin sentence. From the point of view of practical flight operations, the optimum discontinuous curve $1MN2$ is to be substituted with a feasible continuous trajectory, by eliminating the corners M and N and by introducing convenient *transition paths* between the branch $\omega = 0$ (MN) and the two end portions ($1M$ and $N2$) of the Eulerian solution. It is obvious that the above transition patterns must be compatible with the structural limitations of the aircraft, with the physiological ability of the pilot to withstand accelerations, with the stalling behavior, and with the thrust-drag characteristics of the aircraft.

At the present time the writer is collaborating with Professor Placido Cicala of the Politecnico di Torino, Italy, in an attempt to solve the minimal problem under more general hypotheses. Preliminary analyses (14) indicate that if the equation of the motion along the normal to the flight path is written as $L - mg = 0$, all the solutions indicated in Table I remain formally true, provided D be substituted in place of D_0 in the analytical expressions for the arcs $1M$, MN, and $N2$. When, on the other hand, the equation of the motion on the normal to the flight path is used in its exact form [3], the Eulerian trajectory is defined by a sixth-order system of nonlinear differential equations integrable, in general, only by approximate methods. The results of such an investigation will be communicated at an early date.

APPENDIX A

Proof of the Minimal Character of the Path 1MN2

1 Introduction

The results of Table 1 and of Figs. 1, 2, 3 of the main part of the paper may be justified in two ways: (a) by means of indirect variational methods (16), i.e., by formulating the minimal problem as a problem of Mayer type and by using Euler's equations in combination with the Lagrange multipliers; (b) by means of Green's theorem and of the special properties of the function

$$\omega(V, h) = \frac{\partial \Psi}{\partial V} - \frac{\partial \Phi}{\partial h} \quad \ldots\ldots\ldots\ldots [A\text{-}1]$$

where Φ and Ψ are defined by Equations [8] and [9].

The methods (a) and (b) give identical results. The second one, which is here explained, has been already used by the writer in (1) and (4), for the case of a constant mass aircraft.

Green's theorem leads to a straightforward proof of the minimal nature of the path $1MN2$ and is of particular usefulness in cases where limitations are imposed to the class of arcs investigated, such as $h_1 \leq h \leq h_2$ (paths internal to the region of space limited by the horizontal planes $h = h_1$ and $h = h_2$).

II *Properties of the Function* $\omega(V, h)$

Because of the hypothesis $D = D_0$ and of the relationships

$$\frac{\partial \Psi}{\partial V} = \Psi^2 \qquad \frac{\partial}{\partial V}\left(\frac{DV - TV}{g}\right) \ldots\ldots\ldots [A\text{-}2]$$

$$\frac{\partial \Phi}{\partial h} = \Phi^2 \qquad \frac{\partial}{\partial h}(D - T) \ldots\ldots\ldots\ldots [A\text{-}3]$$

Equation [A-1] may be rewritten as

$$\omega(V, h) = \frac{\Psi^2}{g}\left[\frac{V^2}{g}\frac{\partial(T - D_0)}{\partial h} + \frac{\partial}{\partial V}(D_0 V - TV)\right] \ldots [A\text{-}4]$$

It is of particular interest to determine the locus of the points of the (V, h)-plane where $\omega = 0$. Such a locus is defined by

$$\frac{\partial}{\partial V}(D_0 V - TV) + \frac{V^2}{g}\frac{\partial(T - D_0)}{\partial h} = 0 \ldots\ldots [A\text{-}5]$$

Equation [A-5] admits in general more than one solution $V(h)$, depending on the shape of the drag function $C_{D0} = f(M)$. The solution corresponding to lower speed is here designated by $V_{\mathrm{I}}(h)$. Successive solutions (if they exist) are designated by $V_{\mathrm{II}}(h)$, $V_{\mathrm{III}}(h)$, $V_{\mathrm{IV}}(h)$, etc., where by convention $V_{\mathrm{I}}(h) < V_{\mathrm{II}}(h) < V_{\mathrm{III}}(h)$, etc. The (V, h)-plane may therefore be divided into regions whose denomination is as follows: A denotes the region bound by the curves $V = 0$ and $V_{\mathrm{I}}(h)$; B refers to the region between $V_{\mathrm{I}}(h)$ and $V_{\mathrm{II}}(h)$; A' denotes the region between $V_{\mathrm{II}}(h)$ and $V_{\mathrm{III}}(h)$; B' refers to the region between $V_{\mathrm{III}}(h)$ and $V_{\mathrm{IV}}(h)$, etc. (Fig. 7).

A numerical analysis shows that the function ω is negative in the region A, positive in the region B, again negative in the region A', positive in the region B'.

III *Admissible Displacements*

Consider an aircraft having the state of flight (V, h) at time instant t and assume $T > D_0$ as is the case for climbing flight.

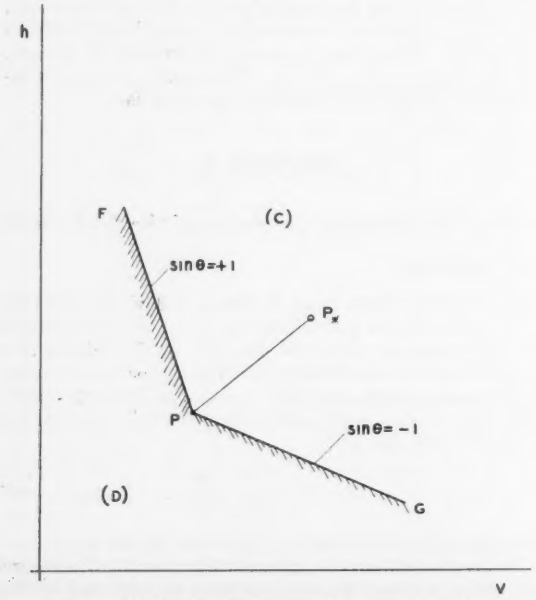

Fig. 6. Admissible displacements in the (V, h)-plane

At time instant $t_* = t + dt$, the aircraft has reached the new state of flight (V_*, h_*) according to the maneuver performed by the pilot. Not all the displacements $\overline{PP}_*$ are physically possible. As a matter of fact, the equation of the motion on the tangent to the flight path

$$\frac{dh}{dV} = \frac{V}{[(T - D_0)/m \sin\theta] - g} \ldots\ldots\ldots [A\text{-}6]$$

states that for given values of h, V, m the derivative dh/dV is a function of $\sin\theta$. As a consequence, all the possible displacements $\overline{PP}_*$ belong to the region C bounded by the two limiting displacements $\overline{PF}$ and $\overline{PG}$ corresponding, respectively, to $\sin\theta = +1$ and to $\sin\theta = -1$ (Fig. 6).

If real solutions are searched, the inequality $-1 \leq \sin\theta \leq 1$ is to be accounted for at any point of the flight path. If, in addition the limitation $h_1 \leq h \leq h_2$ is imposed to the flight path, the following inequality is also to be considered: $0 \leq \sin\theta \leq 1$, at points 1 and 2.

IV *Minimal Proof*

The optimum speed-height relationships $1MN2$ are described in Table I for twelve possible cases of flight. The minimal proof is here offered for one of these twelve conditions. The technique is analogous for the other eleven cases, being based on the considerations of sections II and III and on the application of Green's theorem.

The demonstration offered here refers to case I, $h_1 \leq h \leq h_2$, i.e., to the acceleration and climb from low speed and low altitude to high speed and high altitude of a rocket-powered aircraft utilizing paths internal to the region of space bound by the horizontal planes corresponding to the terminal altitudes. In addition, only flight paths internal to the regions designated by A and B are here considered.

The optimum path is composed of three arcs: an initial arc $1M$ of equation $h = h_1$; a central arc MN of equation $\omega = 0$; a final arc $N2$ of equation $h = h_2$. This statement may be proved, by comparing the special path $1MN2$ with the arbitrary but physically possible path $1K2$ and by showing that the following inequality holds (Fig. 7)

$$(\Delta t)_{1K2} - (\Delta t)_{1MN2} > 0 \ldots\ldots\ldots\ldots [A\text{-}7]$$

The time Δt being a monotonically increasing function of the integral I, it follows that the inequality [A-7] is equiva-

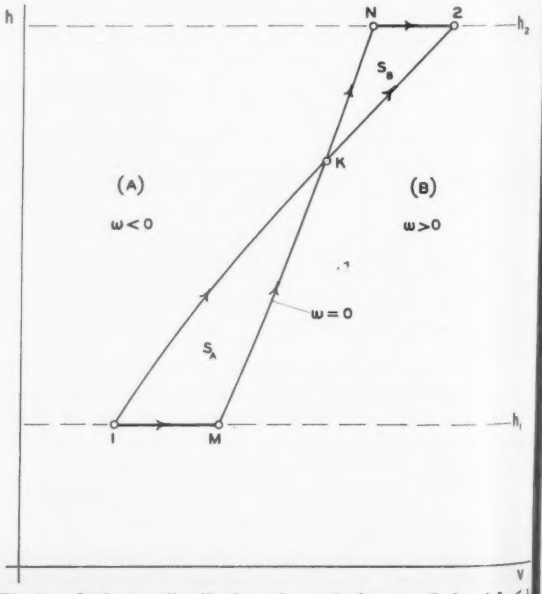

Fig. 7 Optimum distribution of speeds for case I, $h_1 \leq h \leq h$

lent to the other

$$\Delta I = \int_{1K2} (\Phi V' + \Psi)\, dh - \int_{1MN2} (\Phi V' + \Psi)\, dh > 0. \quad [A\text{-}8]$$

i.e.,

$$\Delta I = \oint_{1K2NKM1} (\Phi\, dV + \Psi\, dh) > 0 \ldots\ldots [A\text{-}9]$$

To prove the inequality [A-9], the above line integral is now separated into two cyclic integrals associated with the patterns $K2NK$ and $K1MK$

$$\Delta I = \oint_{K2NK} (\Phi\, dV + \Psi\, dh) - \oint_{K1MK} (\Phi\, dV + \Psi\, dh) \quad \ldots\ldots [A\text{-}10]$$

By using Green's theorem, the afore-mentioned integrals are now transformed into two surface integrals associated with the areas S_A and S_B internal to the contours $K1MK$ and $K2NK$:

$$\Delta I = \iint_{S_B} \left(\frac{\partial \Psi}{\partial V} - \frac{\partial \Phi}{\partial h}\right) dV\, dh - \iint_{S_A} \left(\frac{\partial \Psi}{\partial V} - \frac{\partial \Phi}{\partial h}\right) dV\, dh \ldots [A\text{-}11]$$

i.e.,

$$\Delta I = \iint_{S_B} \omega\, dV\, dh - \iint_{S_A} \omega\, dV\, dh \ldots\ldots [A\text{-}12]$$

The function ω being positive in the region B and negative in the region A (section II), it follows:

$$\Delta I > 0 \ldots\ldots [A\text{-}13]$$

which proves the inequality [A-9] and therefore the minimal character of the path $1MN2$.

The same method may be easily extended to other cases of flight. For instance, if the limitation $h_1 \leq h \leq h_2$ is lifted, the optimum technique of flight changes, in the sense that the horizontal branches $1M$ and $N2$ modify into two diving paths starting at 1 and arriving at 2. Such a case has been already treated in Ref. (1) utilizing Green's theorem as above in combination with the considerations of section III concerning the admissible displacements of the aircraft in the (V, h) plane.

APPENDIX B

Elaboration of the Analysis Leading to Equation [6]

The equation of the motion on the tangent to the flight path [2] may be rewritten as follows after accounting for Equations [8] and [9]

$$\frac{1}{mV \sin\theta} - (\Psi + \Phi V') = 0 \ldots\ldots [B\text{-}1]$$

The above equation and the relationship between rate of climb, velocity modulus and path inclination ($dh/dt = V \sin\theta$) yield

$$\frac{dt}{m} = \frac{dh}{m\, V \sin\theta} = (\Psi + \Phi V')\, dh \ldots\ldots [B\text{-}2]$$

If Equation [B-2] is integrated accounting for Equation [4], the following result is obtained

$$-\frac{1}{\sum \dot{m}_p} \log_e \frac{m_0 - t_2 \sum \dot{m}_p}{m_0 - t_1 \sum \dot{m}_p} = I \ldots\ldots [B\text{-}3]$$

where

$$I = \int_{h_1}^{h_2} (\Psi + \Phi\, V')\, dh \ldots\ldots [B\text{-}4]$$

Equations [4] and [B-3] yield

$$\Delta t = t_2 - t_1 = \frac{m_1}{\sum \dot{m}_p} \left\{ 1 - \exp\left(-I \sum \dot{m}_p\right) \right\} \ldots [B\text{-}5]$$

It is to be noted that the integral [B-4] depends on the history of the motion, i.e., on the three functions $V(h)$, $\theta(h)$, $t(h)$. For the case where Equation [3] is approximated with $L = mg$, I becomes independent of $\theta(h)$. For the other particular case $D = D_0$, I depends only on the velocity distribution $V(h)$.

APPENDIX C

Supersonic Climb[6]

Appendix A contains a proof of the minimal character of the path $1MN2$ under several restrictions, most important of which is the fact that the investigation is confined to the category of arcs internal to the regions A and B.

When the above limitation is lifted, the demonstration of Appendix A is no longer valid. The most convenient way for handling the minimal problem consists of using the indirect methods of the Calculus of Variation, as recently done in (14, 15, and 16). In (16) it is shown that if no limitations are imposed to the geometry of the flight path, the Eulerian solution is defined by an equation of the type $\omega \cos\theta = 0$, which is a curve composed of a combination[7] of vertical paths ($\cos\theta = 0$) and climbing flight along $\omega = 0$.

If the equation $\omega = 0$ admits one single solution $V_I(h)$, the optimum paths are of the type shown in Figs. 1, 2, and 3 of the present report.

If, on the other hand, equation $\omega = 0$ admits several solutions $V_I(h)$, $V_{II}(h)$, $V_{III}(h)$, $V_{IV}(h)$ . . . . , the situation is as follows: $V_I(h)$ is a pattern of minimum time, $V_{II}(h)$ is a path of maximum time; $V_{III}(h)$ is another pattern of minimum time, etc.

A numerical analysis shows that in general $V_I(h)$ is subsonic-transonic, while $V_{III}(h)$ is supersonic. Quite often the rates of climb along part of $V_{III}(h)$ are negative. For high values of the parameter T/pS, however, the rates of climb along $V_{III}(h)$ may become positive, so that a supersonic climb is physically possible.

The next step should be to decide whether it is convenient to climb along $V_I(h)$ or to climb along $V_{III}(h)$ or to climb along a combined pattern which is composed of a part flown along $V_I(h)$ and a part flow along $V_{III}(h)$. Should the third alternative be of engineering interest, another question is to establish the special altitude at which it is convenient to stop the subsonic climb along $V_I(h)$ and to dive to the supersonic region.

To clarify the above problem, the author has carried out a number of preliminary computations for an aircraft having a thrust loading $T/S = 50$ lb/sq ft, and has investigated the region between sea level and $h = 60{,}000$ ft for the following boundary conditions: $M_1 = 0.5$; $h_1 = 0$ ft; $M_2 = 2.8$; $h_2 = 60{,}000$ ft. Results indicate that a subsonic climb along $V_I(h)$ is to be preferred to a supersonic climb along $V_{III}(h)$. The writer, however, is unwilling to derive a general conclusion from one particular set of calculations and thinks that the proposed question requires further investigation.

(Continued on page 399)

[6] This section of the paper has been written at the suggestion of Professor D. O. Dommasch, of Princeton University.

[7] The above result may also be derived by using a modified form of the demonstration of Appendix A, based on Green's theorem.

Development of a Stabilization System for the Viking Rocket

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The unconventional flight path of the Viking, viz., a high altitude nearly vertical trajectory, results in some unusual problems in the design of an automatic stabilization system. In the present vehicle these problems are solved by employing three separate subsystems. First, there is the motor control system which obtains corrective moments by altering the line of thrust of the liquid rocket engine. The second system, the aerodynamic roll system, employs movable tabs attached to two of the fins. Finally there is a thrust reaction system which obtains control moments through the use of small jet motors. Design of the first two subsystems was based on the familiar frequency response techniques, while automatic computers and nonlinear methods were required for the third system. Results of flights to date indicate that the basic approach was sound. However, experience gained on the first nine rockets has shown the need for greater emphasis on reliability, ease of adjustment, and interchangeability of system components during the early phases of the program.

The Viking Rocket

IN December 1945, the Rocket Sonde Research Section of the Naval Research Laboratory was formed for the purpose of conducting high altitude atmospheric research by use of rockets. During the initial phases of the research program, captured German V-2 rockets were employed to carry the necessary instruments aloft. However, the German rockets were limited both in quantity and usability, so the Naval Research Laboratory established a requirement for a rocket designed specifically for upper air research.

As originally conceived, the Viking (then called HASR-II) was to carry instrument payloads up to 500 lb to an altitude of 100 miles along a nearly vertical trajectory. The desired trajectory was to be maintained by a self-contained automatic stabilization system. Aerodynamic stability was to be provided through the use of fins.

The propulsion system of the Viking, like that of the V-2, was to consist of a liquid rocket power plant which employed a steam-driven pumping system to deliver the propellants (alcohol and liquid oxygen) to the thrust cylinder.

To obtain a vehicle meeting NRL's requirements, the Office of Naval Research and The Glenn L. Martin Company signed a contract in the summer of 1946 which provided for the design, manufacture, and flight test of ten rockets. Since much of the necessary design data could be obtained only through flight test, the contract provided for the incorporation of changes as flight data became available. This concept of continued test and modification has been a basis for the program philosophy.

Power plant development was conducted under a separate contract between the Bureau of Aeronautics and Reaction Motors, Inc. When the development program was completed, power plants for the rockets were to be furnished by direct subcontract between Martin and R.M.I.

Presented at the ARS Ninth Annual Convention, New York, N. Y., November 30–December 3, 1954.

[1] Senior Sales Representative. Mem. ARS.

Before we consider the Viking stabilization system in detail, let us first examine the general characteristics of the rocket. As shown in Fig. 1, the present Viking is a cone-tipped cylinder approximately 42 feet long and approximately 4 feet in diameter, having four removable delta planform fins attached to the aft end of the body. It is apparent

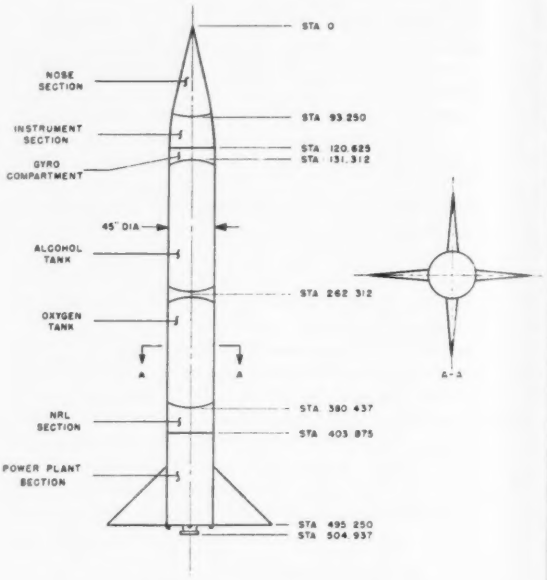


Fig. 1 General configuration

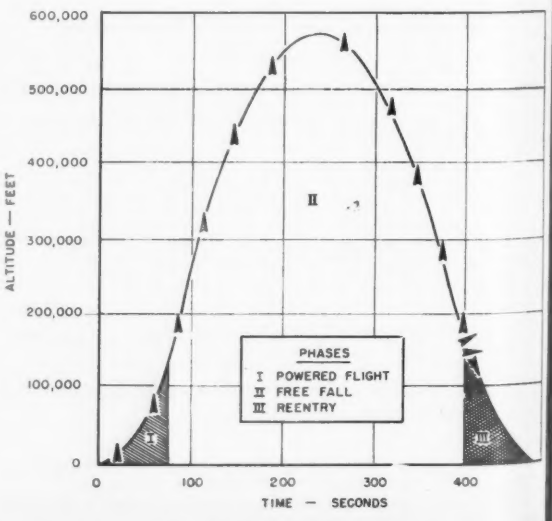


Fig. 2 Typical flight path

from the diagram that the greatest portion of the vehicle is used to carry fuel for the liquid rocket thrust cylinder. This fact becomes even more evident when the 3000-lb weight of the empty rocket (including instrument payload) is compared to the take-off gross weight (15,000 lb). Most of the NRL research instruments are carried in the forward instrument section. In addition, cameras are mounted in the tail section to photograph the earth from high altitude.

The flight path of the Viking may be conveniently divided into three phases, as shown in Fig. 2. During the first phase, the 20,000-lb thrust engine accelerates the rocket to a maximum speed of approximately 4000 mph. Then the rocket coasts through the utter silence of the upper atmosphere, passes through its zenith, and returns toward the earth. Finally, the atmosphere is re-entered, and the vehicle enters its final phase of flight.

Automatic Stabilization

In order that the NRL experiments be carried out successfully, the automatic stabilization system must control the rocket's attitude during the first two phases of flight. The problem is somewhat complicated by the variation of missile dynamics during flight. At take-off, the forward velocity is so low that aerodynamic forces are negligible, and the rocket behaves as a pure inertia. As the speed increases, aerodynamic forces become significant, and the equations of motion of the vehicle become more complicated. Later the lack of air at the upper altitudes reduces these forces until the rocket behaves as a pure inertia again.

In the Viking, pitch is defined as motion in an N-S plane about a horizontal axis through the center of gravity of the rocket. Yaw is similarly defined for motion in an E-W plane, and roll is rotation about the vehicle's longitudinal axis.

Since the control systems for pitch and yaw are identical, only the pitch system will be discussed.

The stabilization system may be divided into three separate subsystems—the motor control system, the aerodynamic roll system, and the hydrogen peroxide thrust reaction system. The first two systems provide control during the major portion of the first phase of flight, while the latter system is employed for roll control at take-off and for three axis control during the second phase of flight.

Motor Control

It was initially proposed that the control moments for pitch and yaw be obtained by the deflection of vanes placed in the jet stream. The chief advantage of this system was the experience obtained on the German V-2. However, the disadvantages of this system became apparent when an investigation of alternate control methods was conducted. When a gimballed motor system was compared with the jet-vane method, the following disadvantages of the latter system were discovered:

1 A considerable weight penalty.
2 A fairly lengthy development program.
3 A decided question as to vane durability.
4 A reduction of specific impulse due to vane drag in the jet stream.
5 A relative complexity of the jet-vane system.

In addition, the adaptability of the gimballed motor offered greater promise for future developments. Consequently, the motor was mounted in a gimbal structure, and control moments were obtained by deflecting the entire motor. The method employed for motor deflection will be discussed in conjunction with the description of the pitch system.

The pitch control system (Fig. 3) comprises the pitch pickoff of the vertical gyroscope, the pitch amplifier, and a packaged unit composed of an electro-hydraulic actuator and follow-up potentiometer.

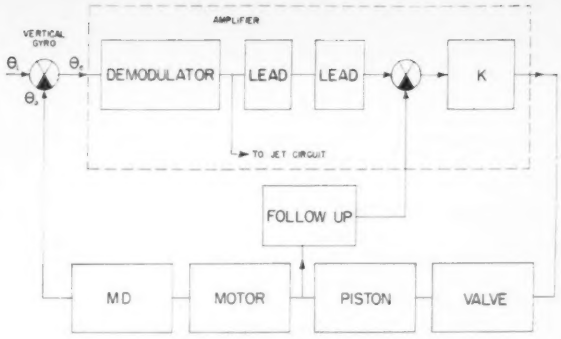


Fig. 3 Motor control system

If the pitch angle of the rocket differs from the gyro reference angle, an error voltage appears at the output of the vertical gyro. For small error angles, the amplitude of this 400 cycle voltage is directly proportional to the error angle. The gyro voltage is applied to the pitch amplifier where it is demodulated, modified by lead circuits, and amplified to a level sufficient to drive the pitch actuator (Fig. 4). This latter

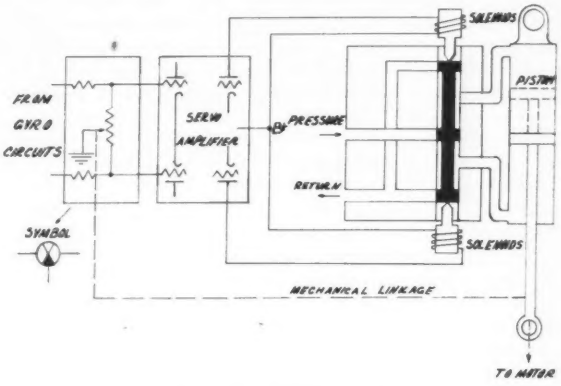


Fig. 4 Electro-hydraulic servo

unit comprises an electro-hydraulic transfer valve, a piston actuator, and a follow-up potentiometer. The error signal from the amplifier produces an unbalance in the current through the valve solenoids which results in movement of the valve spool. When the spool moves, the pressure and return ports are uncovered and oil flows to the piston actuator. As the actuator moves the motor to obtain a corrective moment, it simultaneously positions the follow-up potentiometer. The follow-up signal is then fed back to the amplifier so that the motor deflection is proportional to the error signal. The moment produced by motor deflection rotates the rocket until both the rocket and motor deflection angles are zero. If a moment exists because of an aerodynamic unbalance, the rocket flies with a slight error angle so that a counter moment is produced.

Synthesis of the motor control system was done by the familiar frequency response method. This synthesis was based on the assumptions generally employed in servomechanism design. These assumptions are:

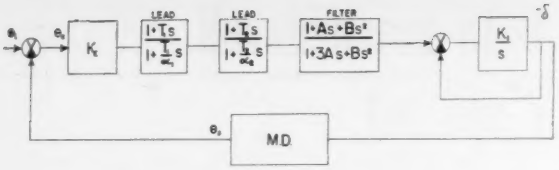
1 The system may be completely described by a set of linear differential equations with constant coefficients.

2 The system transfer function approaches a constant (or zero) as the complex argument s approaches infinity.

3 There is no interaction between elements in the block diagram.

4 The effect of external disturbances such as noise and load torques may be neglected.

The transfer functions of system components in terms of



FLIGHT CONDITION	MISSILE DYNAMICS
TAKEOFF	$\frac{K_3}{S^2}$
MACH 1.5	$\frac{K_3S + K_4}{K_5S^4 + K_6S^3 + K_7S + K_8}$
CUTOFF	$\frac{K_3}{S^2}$

Fig. 5 Motor control system block diagram

the Laplace variable are shown in Fig. 5. The block labelled M-D represents the missile dynamics. No transfer function is shown in this block because the missile dynamics are not constant. As previously mentioned, the missile behaves as a pure inertia at take-off and after it has left the atmosphere, while the dynamics are much more complicated when aerodynamic forces are present. Because of the wide variation of missile dynamics it was not possible to design the system for optimum performance at any one flight condition without programming changes in gain and/or lead circuits to provide stability at the other points. Since programming of system parameters was not considered desirable, a compromise design evolved which provided adequate, though not optimum, stability for all flight conditions.

System synthesis was further complicated by the manifestation of a severe vibration problem during vertical testing of Viking No. 1. It was discovered that the rocket body was a fairly efficient transmitter of the vibration of the motor's gimbal structure at the latter's resonant frequency. This vibration produced a gyro output signal which was fed back to the motor through the amplifier so that the original vibrations were re-enforced. The result was a rather violent vibration of the entire rocket. Considerable effort has been spent in the design of filters to minimize the chatter problem.

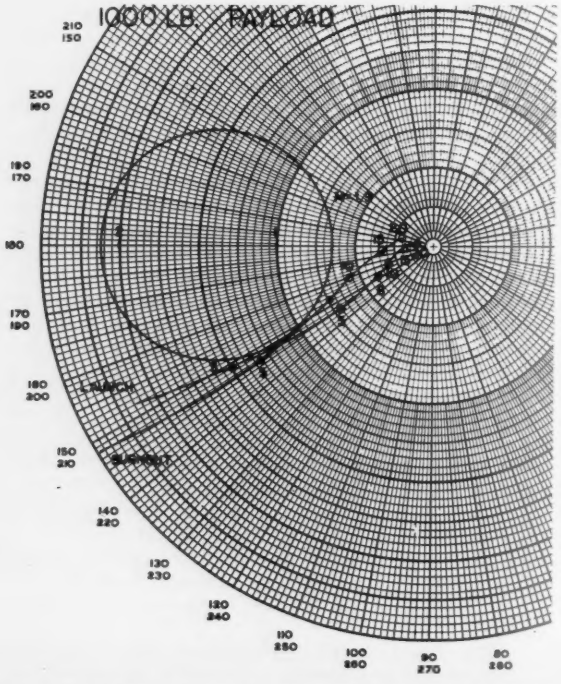


Fig. 6 Pitch control system compensated open loop response

The transfer function of the existing filter is included in the system block diagram.

After adequate system stability was demonstrated by Nyquist criteria, transient analyses of system performance were conducted on automatic computers. The Nyquist diagrams are shown in Fig. 6, while a typical transient response is illustrated in Fig. 7.

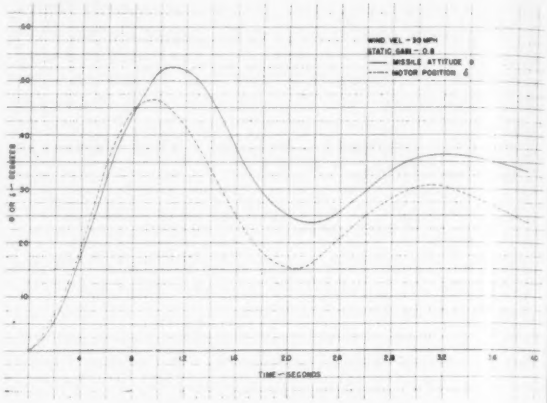


Fig. 7 Typical launch transient

The major source of trouble during field operations has been the chatter problem just mentioned. However, a number of minor difficulties encountered in test and adjustment of the system have resulted in changes in the hardware. An attempt has been made to select reliable components and noise-free tubes, and component packaging has been revised to increase serviceability and ease of assembly.

The over-all performance of the pitch and yaw systems has demonstrated the soundness of the control method and the adequacy of the approach to synthesis. In no case has a failure resulted because of erroneous initial assumptions or deficiencies in the design method.

Aerodynamic Roll Control

At one time during the initial design, it was thought that control of roll rate, to 10 rpm or less, would be satisfactory. However, NRL instrumentation requirements soon made it apparent that the rocket's roll position would have to be held nearly constant. Consequently, roll control tabs were incorporated in the design of two of the fins.

The roll control system comprises the roll gyro, roll amplifier, roll transfer valve, and the tab actuators. System operation is similar to that of the motor control system in that a roll error results in a 400 cycle gyro signal which is modified by an amplifier and then applied to a solenoid operated valve. When the valve ports are opened, hydraulic fluid flows to the piston-type actuators which move the tabs. The tabs are deflected so that a roll moment is produced which rotates the rocket back to the desired position.

Since the design of the roll system was performed in the same manner as that for the motor control system, a detailed consideration of the method will not be repeated here.

In general, system performance has been satisfactory. There have been some difficulties with components which have resulted in improved packaging and better adjustment procedures. However, as in the case of motor control, there have been no failures due to erroneous initial assumptions or faulty design methods.

Hydrogen Peroxide Jet Control System

The third system to be considered obtains control moments through use of small thrusts jets. The thrust energy for

these jets is furnished by catalytic decomposition of concentrated hydrogen peroxide. This system is required for roll control at launch, when aerodynamic forces are near zero because of the small forward velocity, and for three axis control after burnout when the rarefied atmosphere will not support an aerodynamic system.

Let us first consider the operation of the pitch/yaw or tumble-jet system. When cutoff of the main thrust cylinder occurs, the contacts of the tumble-jet relays are energized. As shown in Fig. 8, the demodulated gyro output is applied to the tumble-jet circuit as well as to the motor amplifier at all times so the jet relays open and close in response to gyro signals. However, the jet valves are not actuated prior to cutoff because of the absence of voltage at the relay contacts. During the post cutoff period, closure of a jet relay applies voltage to the proper solenoid valve, and peroxide flows to the jet motor. The peroxide is then decomposed into steam and oxygen and exhausted through a nozzle to produce a corrective moment.

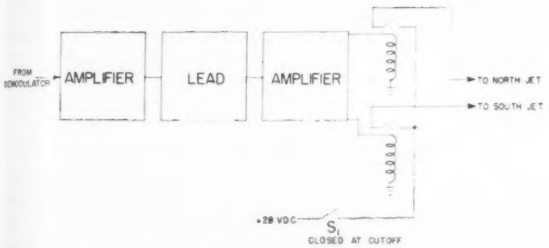


Fig. 8 Pitch tumble-jet system

Originally this system was designed on an REAC (Reeves Electronic Analog Computer) with the actual amplifiers and relays included in the loop. This approach was quite satisfactory from a design standpoint but was time-consuming and rather wasteful of the computing equipment. Consequently, several methods of analyzing nonlinear systems were investigated, and the results were compared with the REAC solutions. The most promising method uncovered to date is the phase plane approach. In this method a plot of velocity vs. the corresponding displacement defines a "phase plane." With a little experience, it is possible to visualize the effect of parameter changes on system operation by study of the phase plane diagrams. As an example, let us consider the problem of determining the steady-state operation of the tumble-jet system. In Fig. 9 the pitch error angle is the abscissa and the pitch angular velocity is the ordinate. (Nondimensional variables have been employed to permit the use of a template for several different problems.) In general, relay dead-spot and hysteresis may be represented by a dead zone. In this particular system, the effect of the lead circuit is to modify the dead zone boundaries as shown. Since a constant corrective moment is applied when the jets are on, it may be shown that the descriptive point in the phase plane follows a parabolic trajectory during operation outside the dead zone. When the dead zone is entered, the corrective moment is removed, and the angular velocity remains constant. Consequently, the point in the phase plane follows a straight line parallel to the horizontal axis.

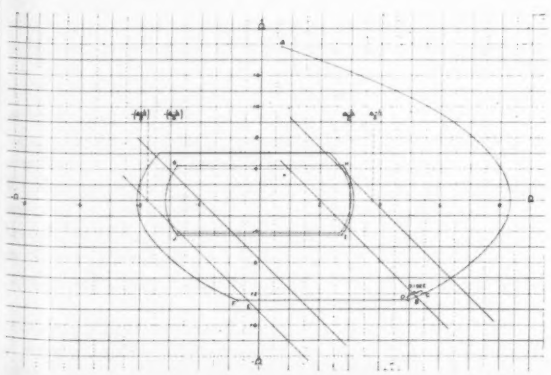


Fig. 9 Typical phase plane plot

Let us begin our analysis at point A in Fig. 9. Since this point is outside the dead zone, the descriptive point follows a parabola until it reaches the boundary line at B. One would normally expect the relay to open at this point. However, second order effects shift the drop-out point back along the trajectory to point C. (This shift becomes negligible if the time interval from A to B is much larger than the time constant corresponding to the second break point of the lead circuit.) Then the descriptive point follows the parabolic trajectory for a short distance beyond the relay drop-out point because of the time delay between relay opening and zero thrust. When zero thrust occurs at point D, the descriptive point moves across a constant velocity line where it intersects the relay pull-in line at point E. Since the jet thrust does not build up instantaneously, the descriptive point continues along the horizontal line to point F. Then, another constant acceleration trajectory is followed until the relay drops out again. This process continues until successive trajectories follow identical paths as indicated by G H I J. The steady-state amplitude may then be determined directly from the phase plane plot, and the period can easily be calculated by transforming the equations of motion back into the time domain.

It is possible to analyze transient performance on the phase plane, but the process is somewhat more complicated since, in general, accelerations are not constant.

When the results of the phase plane analysis were compared with the REAC solution, it was found that the steady-state period and amplitude and the jet-on-time per cycle agreed within two per cent.

Since the analysis of the roll-jet system is similar to that described for the tumble-jet system, a detailed description will not be presented. However, some significant differences in hardware will be mentioned. The vehicle dynamics and expected disturbances in roll require that two lead circuits and two jets be employed for each roll direction. The use of two lead circuits complicates the phase plane diagrams somewhat; however, the results obtained were found to agree with the REAC solution with an accuracy comparable to that achieved for the tumble-jet system.

Unfortunately, very little data have been obtained on the in-flight performance of the jet control system. During the early flights, when a similar system was employed, the power plant was cut off before the rocket left the atmosphere, so operation of the post cut-off system was severely hampered. Special experiments conducted on later models required the introduction of spin about the roll axis during the post cut-off period, so data on jet operation were again inconclusive. Fortunately there were no impediments present on the last two flights. All of the data have not been reduced, so a detailed comparison of actual and theoretical performance cannot be made. However, it may be said that the jet system performed approximately as expected.

Present effort is directed toward increased reliability and repeatability of adjustments, since these items have been troublesome in the past.

Conclusion

The success of the Viking program has proved that the initial assumptions and design method are sound. However, practical problems encountered during operations have shown

(*Continued on page 399*)

Rupture of Heat-Resistant Alloys in Flame Gas Atmospheres

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The rupture of temperature resistant materials, stressed in combustion atmospheres, is reported for two cold-worked commercial alloys at temperatures between 920 C and 1150 C in a burning propane flame. Rupture times of approximately 30 seconds to one hour were obtained, covering a range of 10 stresses between 4300 psi and 9680 psi. Data are compared with conventional stress-rupture and creep data, and are in general agreement. Experimental evidence is obtained indicating that the activation energy of the stress-rupture process (under the above conditions of heating and atmosphere) is not constant, and may be stress dependent. The power function of the stress term in the equation

$$1/t = Be^{-Q/RT}\sigma^n$$

is also shown to be slightly temperature dependent.

It is concluded that the rate process equation may be useful in the interpretation of stress-rupture data but extrapolation is not accurate.

Introduction

THE application of rate-process theory to the high temperature failure of metals by rupture, and creep, has been the subject of much research and interest.

However, research in this laboratory was conducted in an effort to determine the effects of combustion atmospheres on the rupture life of a stressed metal, when the metal is in the presence of, and heated by, a gas flame, with the products of combustion available for possible diffusion.

The materials selected for the investigation were commercially available heat-resistant alloys, chromel and nichrome, of the following approximate compositions: chromel: 60 nickel, 15 chromium, 22 iron, 1 silicon, and 0.6 manganese; nichrome: 80 nickel, 17 chromium, 1.3 silicon, 0.6 iron and 0.6 manganese.

Both materials were in wire form, 0.051 in. in diameter, and used in the cold-drawn (as received) condition without further heat treatment or annealing to emphasize any effects of prior cold-working. Room temperature tensile strengths were: chromel: 115,000 psi; nichrome: 107,400 psi.

Procedure

A sample of wire 3 in. long was gripped between small chucks and suspended horizontally over an adjustable laboratory-type gas burner. One chuck was firmly anchored, and the other connected to a vertical static load by means of a lightweight flexible table over a well-lubricated pulley. Rupture times were measured by a stop watch, started when the gas from the burner was ignited. Thus, each time observed in this report includes the time necessary to bring the specimen up to temperature, around 12 seconds.

Temperatures were recorded by means of a chromel-alumel thermocouple spot-welded to each specimen, with each leg of the thermocouple $^1/_8$ in. away from the plane of rupture, so that the break occurred between welds, eliminating the possible catalytic action of the thermocouple wires.

By varying the gas volume as well as the distance from burner to specimen, the temperature of the wire could be varied from 900 C to 1150 C, approximately. The gas used in the burner was, by mass spectrometric analysis, 95 per cent propane and 5 per cent butane. Flame composition was never reducing and the wire was not allowed to enter the unburned portion of the gas.

Each specimen was loaded statically before ignition. Maximum recorded temperatures were reached within 12 seconds, after which inaccuracies were introduced because of thermocouple contamination. Accordingly, the temperatures recorded here are believed to be no better than ± 10 C of actual temperature, although spot checks with a standardized optical pyrometer, with corrections for emissivity based on the Wien equation, were within 5 C of the recorded temperature.

Analysis

It has been shown that stress rupture, as well as creep, of metals, appears to follow rate process law and, in general, to conform with the Arrhenius equation

$$k = se^{-E/RT} \quad \text{(Refs. 1–7)}^2 \quad [1]$$

where k is usually a rate, or reciprocal of time, s is considered a constant, although slightly temperature dependent, E is the energy of activation, R the gas constant, and T the absolute temperature.

In the case of rupture, Equation [1] is

$$1/t = Ae^{-Q/RT} \quad [2]$$

where t is the time to rupture, A is a constant, and Q the activation energy.

The value of the activation energy, or temperature coefficient of the reaction, is determined empirically by plotting the logarithm of the reciprocal of time against the reciprocal of the absolute temperature on linear coordinate paper, the slope of the line formed being equal to $Q/2.3R$.

Fig. 1 shows a typical plot of this type, for nichrome wire, after rupture in the propane flame. This plot and others used for the determination of Q are lines constructed according to the "least squares" method, and are lines of regression of X on Y, since the major errors are in the observation of temperatures. In all cases, the values of the correlation coefficients are from 0.94 to 0.99, and setting a confidence limit of 50 per cent, the probable error in the calculated activation energies reported herein is around 3 per cent.

Fig. 2 shows a family of plots at 5 stresses, for chromel wire, in which two definite slopes are noted (9). The variation in slopes is beyond the calculated error, and the value of Q for each stress is tabulated in Table 1.

Received October 20, 1954.

[1] Metallurgist.

[2] Numbers in parentheses indicate References at end of paper.

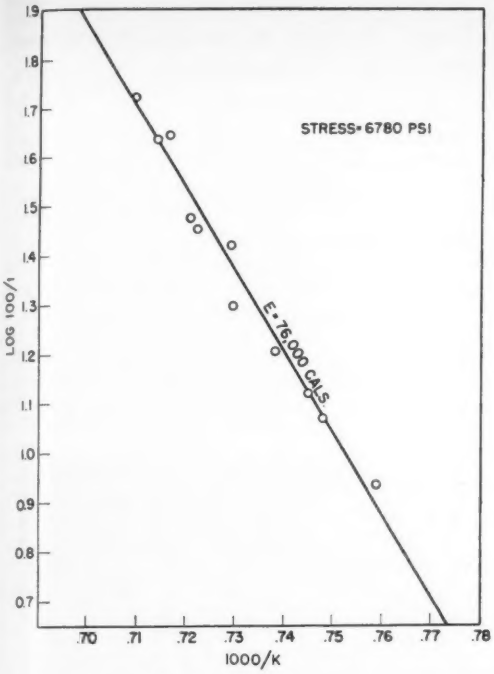

Fig. 1 **Typical Arrhenius plot showing temperature dependence of nichrome at constant stress**

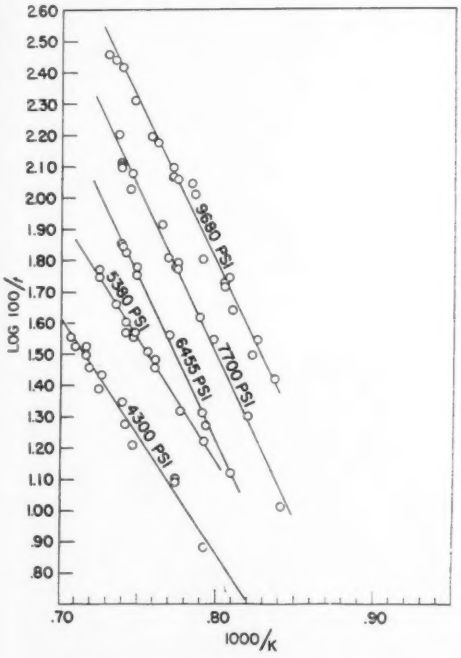

Fig. 2 **Family of plots showing temperature dependence at various stresses for chromel**

Table 1 Chromel wire

Stress, psi	Q, Kcals
4300	34.8
5380	36.9
6455	48.1
7700	48.3
9680	47.1

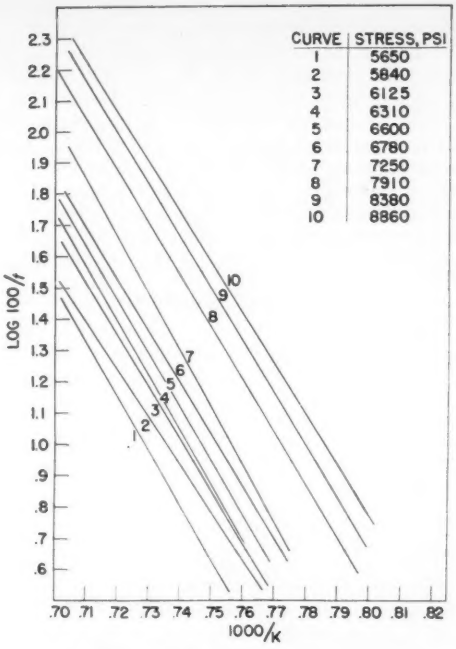

Fig. 3 Family of plots showing temperature dependence at various stresses for nichrome

Fig. 3 is a family of Arrhenius plots for nichrome, over a range of 10 stresses. Individual points have been omitted for the sake of clarity, but each slope represents a plot similar to Fig. 1. It is apparent that here, also, some change in slope occurs as the stress is changed. Values of Q for this material are shown in Table 2.

Table 2 Nichrome wire

Stress, psi	Q, Kcals
5650	79.2
5840	69.7
6125	76.1
6310	80.1
6600	78.8
6780	76.0
7250	83.4
7910	76.4
8380	76.1
8860	73.8

Both tables indicate changes in the value of activation energy with stress; in the case of chromel, Q increases with stress, but only to the extent that another value is reached which, over the range of stress applied, is relatively stable. This would suggest that over 6000 psi, the rate determining mechanism is of a different nature.

In the case of nichrome, Q seems to fluctuate and then decrease with increasing stress. It is interesting to note that Carreker (3), in his study of creep in platinum, shows a decrease in Q for increases in stress, at various strain rates, but no increases. However, the alloys used here were not annealed, and the phenomena may be explained by de Bruyne's (7) hypothesis that the relation between Q and stress may be dependent on the strain energy stored prior to rupture.

The general rate equation

$$k = Ae^{-Q/RT} \quad [3]$$

for the conditions of the above experimental work, can be resolved (8) empirically into

$$1/t = Be^{-Q/RT}\sigma^n \quad [4]$$

where B is a constant, σ is the stress, and n is the stress exponent, usually considered constant. However, Figs. 4 and 5 show the relationship between stress and time at constant temperature. Plots are seen to be linear, with the slope being equal to the value of n in Equation [4]. The relationship is also slightly temperature dependent, in agreement with the general preexponential constant in the Arrhenius equation. Even this slight variation is of some consequence, because of its value exponentially, as may be seen in Table 3.

For comparison, Roberts (6) has found the value of n to be between 3.5 and 4.2, in his studies of creep of magnesium, between 200 F and 500 F, although the relation between exponent and temperature was not linear.

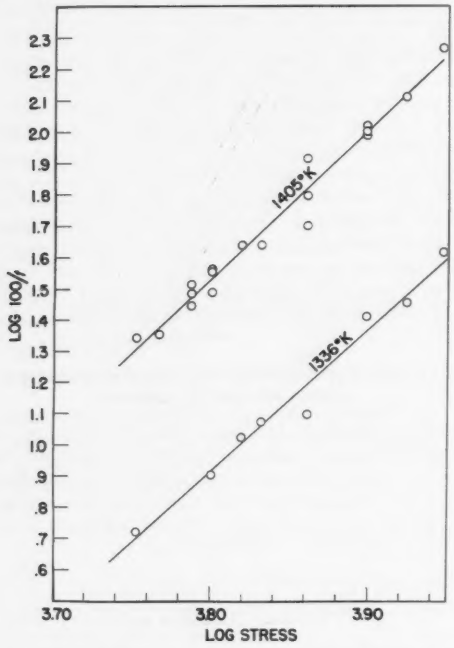

Fig. 4 Stress dependence at constant temperature for nichrome

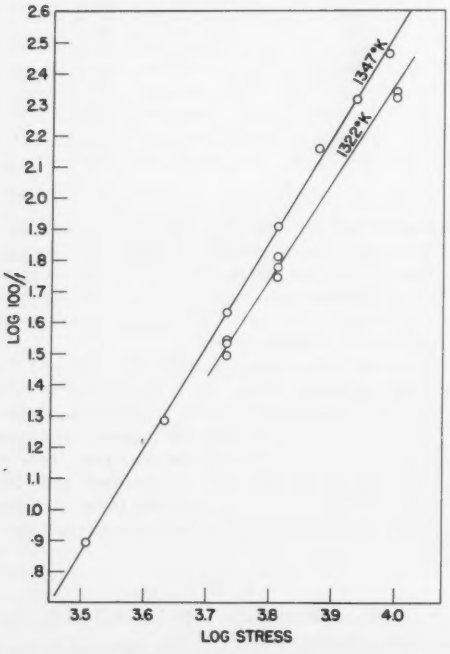

Fig. 5 Stress dependence at constant temperature for chromel

Table 3 Temperature dependence of stress exponent

Alloy	Temperature, °K	n
Chromel	1347	3.3
Chromel	1322	3.1
Nichrome	1405	4.8
Nichrome	1336	4.5

Measurements of wire diameters at the location of rupture did not change appreciably after rupture, so the stress approximates a true, or constant, stress. Reductions in area were of the order of 3 per cent. This may have been due to the embrittling effects of the atmospheric contaminants. Figs. 6 and 7 are typical microstructures of the alloys after exposure to gases and stress. The effect of diffused gases may be seen

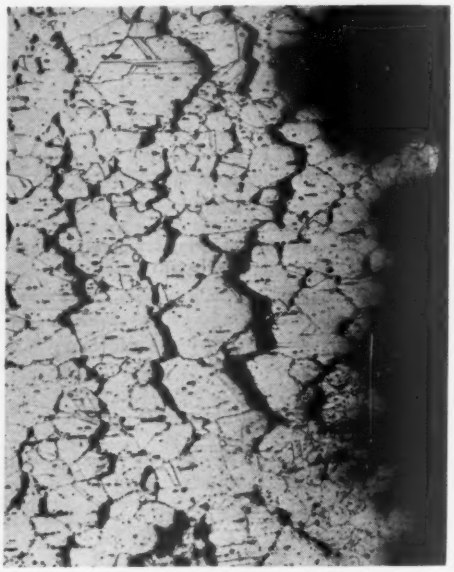

Fig. 6 Nichrome

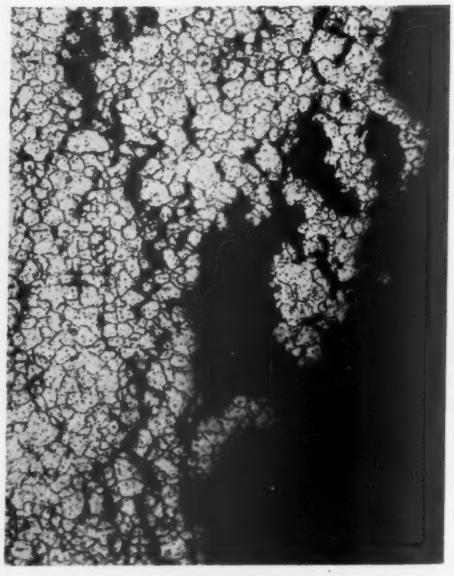

Fig. 7 Chromel

in the presence of voids and the failures are of the intergranular, or high temperature, type.

Conclusions

It may be concluded that accurate extrapolation of data is not possible until further research discloses the relations between stress and temperature, activation energy and stress, and the true meaning of the pre-exponential, if the rate equation is used for the analysis of stress rupture under the conditions of atmosphere and heating described.

Acknowledgment

The author wishes to express his thanks to Dr. James R. McNesby of the Research Department for many helpful discussions and for his interest in the program, and also to the Naval Ordnance Test Station for permission to publish the results.

All photographs are official, U. S. Navy.

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Optimum Climbing Technique for a Rocket-Powered Aircraft

(*Continued from page 391*)

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Development of a Stabilization System for the Viking

(*Continued from page 395*)

that more of the initial effort should have been spent on the development of simplified test procedures, easily serviced components, interchangeable units, and more reliable equipment.

Although the stabilization system, in its present form, is capable of control within the required limits, continual effort is spent in improving system performance through the incorporation of superior components and the application of advanced design techniques. The design has remained in a semi-fluid state throughout the program so that desirable changes could be incorporated. This philosophy is not only feasible but highly desirable in a program of this nature.

Erratum

The following sentence should be added to "Acknowledgment" in the paper, "A Combustor Analysis Method Evolved from Basic Flame Stability and Fuel Distribution Research," by John W. Bjerklie, in the May 1955 issue of JET PROPULSION:

"The concepts for adaptation of fuel distribution methods to velocity profile are due in large part to Eugene B. Zwick, now of American Machine and Foundry Company, Turbo-Engineering Department, Pacoima, Calif."

Technical Notes

On the Classification of Normal Detonation Waves[1]

THOMAS C. ADAMSON, JR.[2], and RICHARD B. MORRISON[3]

University of Michigan, Ann Arbor, Michigan

DETONATION waves usually are classified with respect to the Chapman-Jouguet wave; i.e., a weak detonation wave indicates a final Mach number greater than 1, a Chapman-Jouguet wave indicates a final Mach number of 1, and a strong wave indicates a final Mach number less than 1. Here, the final Mach number refers to the Mach number after the wave, measured with respect to the wave. It has always been a problem to classify the waves mathematically in such a way as to illustrate the above-mentioned distinctions in a simple manner. While a dimensionless heat release parameter seems the obvious parameter to use, the simplest dimensionless group, formed by dividing the heat released per unit mass by the product of a specific heat and temperature, gives no clue as to the limits imposed on the heat release and initial Mach number in the limiting case of the Chapman-Jouguet wave. Furthermore, the computations for the pressure, temperature, and density ratios across the wave are too involved using only this simple parameter. With these thoughts in mind, the following classification is proposed.

Consider a standing wave with incoming velocity U_1, pressure P_1, temperature T_1, and density ρ_1, and outgoing velocity U_2, pressure P_2, temperature T_2, and density, ρ_2.

Note that the results hold for a wave moving with velocity U_w into a medium moving at velocity $\bar{U}_1$ with final velocity $\bar{U}_2$, if the following transformations are used.

$$U_1 = U_w - \bar{U}_1$$

$$U_2 = U_w - \bar{U}_2$$

Considering the wave to be a discontinuity in the flow, the conservation equations written as simple difference equations, and the equation of state supply the four equations necessary to find the four unknowns, P_2, T_2, ρ_2, U_2, in terms of the given quantities, P_1, T_1, ρ_1, U_1, and Q, where Q is the heat released by the unburned mixture per unit mass.

Mass $\quad \rho_1 U_1 = \rho_2 U_2$

Momentum $\quad P_1 + \rho_1 U_1^2 = P_2 + \rho_2 U_2^2$

Energy $\quad C_P T_1 + \dfrac{U_1^2}{2} + Q = C_P T_2 + \dfrac{U_2^2}{2}$

State $\quad P = \rho \dfrac{R_0}{m} T = \rho R T$

Here, C_p is the specific heat at constant pressure, m is the molecular weight, and R_0 is the universal gas constant. For simplicity, C_p and m are assumed constant through the wave.

First, the momentum equation can be written as follows

$$\frac{P_2 - P_1}{P_1} = \frac{\rho_1}{P_1}(U_1^2 - U_1 U_2) = \frac{\gamma}{a_1^2}(U_1^2 - U_1 U_2) \quad \ldots [1]$$

where $a^2 = \gamma RT = \gamma(P/\rho)$ is the local speed of sound, and γ is the ratio of specific heats. Also, since $C_p/R = \gamma/(\gamma - 1)$, the energy equation can be solved for a_2^2

$$a_2^2 = a_1^2 + \frac{\gamma - 1}{2}(U_1^2 - U_2^2 + 2Q) \quad \ldots [2]$$

Finally, the momentum and continuity equations can be solved for $U_1 - U_2$;

$$U_1 - U_2 = \frac{P_2}{\rho_2 U_2} - \frac{P_1}{\rho_1 U_1} = \frac{1}{\gamma U_1 U_2}(U_1 a_2^2 - U_2 a_1^2) \quad \ldots [3]$$

After substituting Equation [2] for a_2^2, Equation [3] may be multiplied by U_1, divided by a_1^2, and rearranged to give an equation in $(U_1^2 - U_1 U_2)$. Thus

$$\frac{U_1^2 - U_1 U_2}{a_1^2} = \frac{(M_1^2 - 1)}{(\gamma + 1)} \left\{1 \mp \sqrt{1 - \frac{2(\gamma + 1)M_1^2}{(M_1^2 - 1)^2}\frac{Q}{C_p T_1}}\right\} \quad \ldots [4]$$

where $M = u/a$ is the Mach number.

The minus sign can be ruled out by considering the case when $Q = 0$ (shock wave) and noting that the minus sign gives the trivial solution $U_2 = U_1$ (no wave).

If one defines, now, a heat release function

$$F(T_1, U_1, Q) \equiv 1 + \sqrt{1 - f} \quad \ldots [5]$$

where

$$f \equiv \frac{2(\gamma + 1)}{(M_1^2 - 1)^2} M_1^2 \frac{Q}{C_p T_1} \quad \ldots [6]$$

Then, substitution of Equation [4] into Equation [1] yields

$$\frac{P_2 - P_1}{P_1} = \frac{\gamma F}{(\gamma + 1)}(M_1^2 - 1) \quad \ldots [7]$$

This relation can be checked by comparing it with normal shock wave theory; in the case of a shock wave, $Q = 0$, so that $f = 0$ and $F = 2$, which gives the correct result. More significant is the fact that $f = 1$ gives the relationship between M_1 and Q for a Chapman-Jouguet detonation wave, which can be seen either by going through the previous derivation for $(U_1^2 - U_1 U_2)$ with $U_2 = a_2$, or by solving directly for the Mach number of a Chapman-Jouguet wave in terms of the heat release. The strong detonation wave then corresponds to $0 < f < 1$, or $1 < F < 2$.

The density ratio can be found by using the continuity equation. Thus

$$\frac{\rho_2}{\rho_1} = \frac{U_1}{U_2} = \frac{U_1^2}{U_1 U_2} = \frac{1}{1 - \dfrac{(U_1^2 - U_1 U_2)}{U_1^2}} \quad \ldots [8]$$

which can be written in the desired terms using Equations [4] and [5].

Also, the temperature ratio can be found using the equation of state and Equations [7] and [8].

(*Continued on page 403*)

Received May 2, 1955.

[1] This investigation was carried out under the sponsorship of Project Squid, ONR Contract N6-ori-105, T.O. iii.

[2] Associate Research Engineer, Aircraft Propulsion Laboratory; Lecturer, Department Aeronautical Engineering.

[3] Supervisor, Aircraft Propulsion Laboratory; Assistant Professor, Department Aeronautical Engineering.

EDITOR'S NOTE: This section of JET PROPULSION is open to short manuscripts describing new developments or offering comments on papers previously published. Such manuscripts are published without editorial review, usually within two months of the date of receipt. Requirements as to style are the same as for regular contributions (see first page of this issue.)

Jet Propulsion News

Alfred J. Zaehringer, American Rocket Company, *Associate Editor*

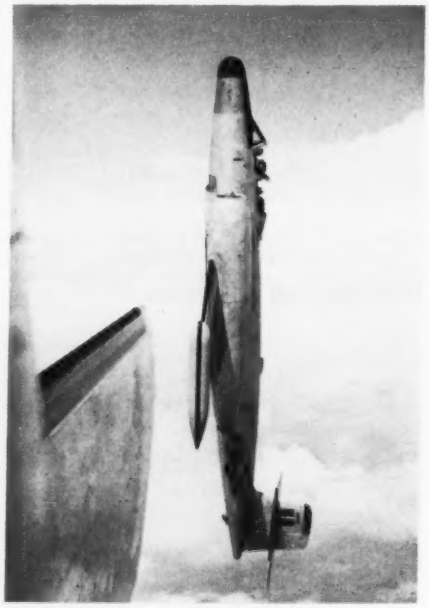
Jet Aircraft, Engines

A NEW official transcontinental (L. A. to N. Y.) speed record was set by the U.S.A.F. in a Republic F-84F Thunderstreak at 652 mph. The 2463 mile course was completed in 3 hr, 46 min.

● Republic Aviation is to develop a photo-reconversion of the F-105 advanced fighter-bomber.

● The Comet Mark 4 is the latest version of the British jet airliner. The new Comet is equipped with Ra 29 Rolls Royce engines and incorporates structural and design improvements, has 10% more range than the Mark 3, and will be able to carry 58 passengers on the London-New York run at better than 500 mph.

● Experimental tailpipe thrust augmentor will be fitted on Canadian Avro CF-100. New augmentor with Marquardt variable area nozzle will up power around 15 per cent. A new Avro craft, the CF-105 long-range interceptor is soon to be tested. Power for the 105 comes from the PS-113 Super Orenda turbojet now being tested. Thrust is expected to be in the 18,000–25,000-lb thrust range.



AVRO Canada

CF-100 heads upstairs

● Jet engines are playing a new role in aviation. Solar Aircraft has pod-mounted its Mars turbojet engine to generate 30 kw DC or 40 kva AC at 25,000 ft for the Convair C-131B flying electronic laboratory. Mars develops 50 hp, weighs only 100 lb, is smaller than a two-foot cube, and operates at 40,000 rpm.

Svenska Aeroplan

Saab 29 jet fighter

● The Swedish Air Force fighter Saab J29 recently set a closed course speed record of 560 mph. A de Havilland Ghost turbojet engine of 5000-lb thrust gives the plane a top speed of about 660 mph. The J29 was the first European swept-wing jet fighter in mass production. Saab 32, a new Swedish fighter, has exceeded the speed of sound in recent tests and is in quantity production.

Svenska Aeroplan

Saab 32 all-weather jet

● Jet engines are propelling test "cars" in tests conducted by All American Engineering Co., Sussex County Airport, Georgetown, Del. Used in development of aircraft arresting gear, the car is held captive to a 5000-ft concrete track.

● A new turbojet engine, the J73 rated at 9000-lb thrust, was announced by G-E. The J73 is a "cannular" engine of a single combustion space containing ten individual "cans." A two-stage turbine is directly connected to the compressor. Basic engine control comes from a hydraulic system. Oil is cooled by engine fuel. Dimensions: diameter, 36.75 in; length, 148 in. Meanwhile, G-E has revealed its new fuel

EDITOR'S NOTE: The information reported in this Section has been selected from approved news releases originating with the Department of Defense, private manufacturers, universities, etc., and from published news accounts in journals and newspapers. The reports are considered generally reliable, although no attempt has been made to verify them in detail.

pump which can feed 86 gpm of jet fuel into the afterburner of the J47-33 turbojet. Driven by air from the main turbine, the pump is mounted inside the fuel tank and is smaller than a swivel-top vacuum cleaner.

The Research Scene

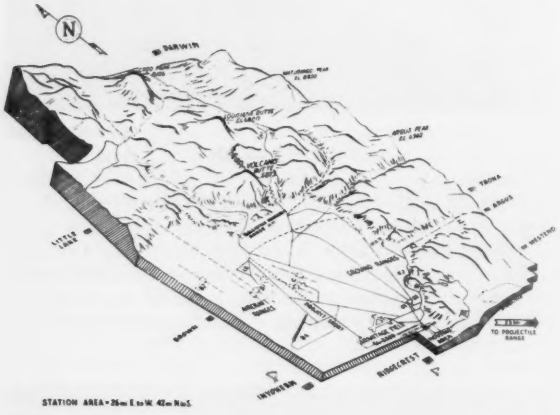
DETECTION of the jet stream, at altitudes of 25,000–40,000 ft, is to be studied by the Cornell Aeronautical Laboratory of Buffalo, N. Y. Installation of electrostatic measuring equipment is to be made in high-flying aircraft to check the hypothesis that the jet stream carries a net electrical charge. Other Cornell projects currently include flight studies of the F-100 at supersonic speeds and wind tunnel tests of the Navy supersonic fighter F9F-9 Tiger.

● The Department of Defense has established a Titanium Metallurgical Laboratory under contract with the Battelle Memorial Institute, Columbus, Ohio. The laboratory will provide a source of technical information on titanium production and application.

● Ceramic fibers, known commercially as Fiberfrax, are to be manufactured by the Carborundum Co., Niagara Falls, N. Y. Blown from molten aluminum oxide and silica, Fiberfrax is a cottonlike mass of extremely small fibers which remain stable at temperatures up to 2300 F. A wide variety of forms is available.

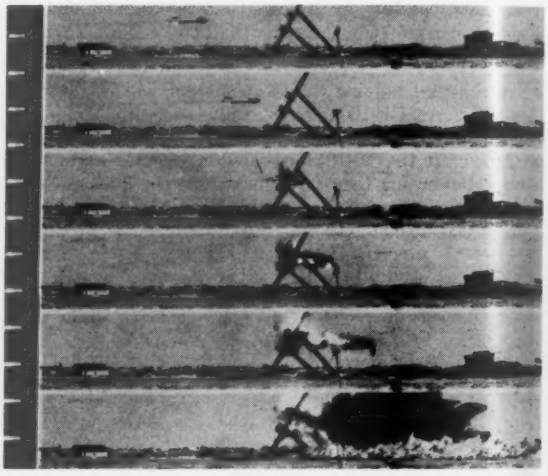
● A solid propellant charge provides power for personnel seat capsule ejections in a new design by Reaction Motors. Downward catapult tests are to be made from a B-47 bomber.

MOJAVE MARVEL



U. S. Navy

Lay of the land . . . U. S. Naval Ordnance Test Station is shown here in relief. Located 160 miles N. E. of Los Angeles in Mojave Desert at China Lake, NOTS has an area of over 1000 square miles. Other NOTS installations are located at Pasadena, Long Beach, and San Clemente Island. Established in 1943, the mission of NOTS is to develop and test rockets and guided missiles. The China Lake community now numbers more than 10,000.

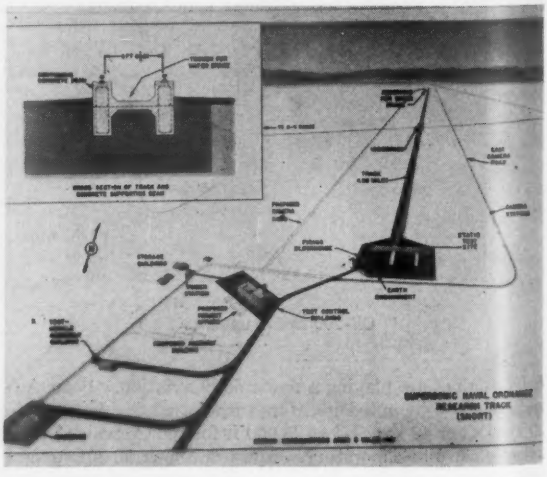


U. S. Navy

Tim tears target . . . On free-flight projectile range rockets such as the "Tiny Tim" 11.75-in. air-to ground rocket are given tests. Tim, Mighty Mouse 2.75-in. air-to-air rocket, and RAM, 6.5-in. air-to-ground rocket, were developed here.

U. S. Navy

High altitude chamber . . . Environmental testing of rockets and components is carried out at the Michelson Laboratory, the research center of NOTS. It is equipped for basic and applied research in physics, chemistry, aerophysics and ballistics, propulsion, fire control and guidance.



U. S. Navy

SNORT . . . Built to bridge the gap between wind tunnel and free-flight testing is the new Supersonic Naval Ordnance Research Track at China Lake. Ruggedly built, it affords intact recovery of test items and has instrumentation approaching laboratory conditions.

On the Classification of Normal Detonation Waves

(*Continued from page 400*)

Finally, the Mach number behind the wave can be computed by rearranging Equations [4] and [5]; thus

$$\frac{U_1^2 - U_1U_2}{a_1^2} = \frac{(M_1^2 - 1)}{(\gamma + 1)}F$$

or

$$M_1^2 - M_1M_2\frac{a_2}{a_1} = \frac{(M_1^2 - 1)}{(\gamma + 1)}F$$

so that

$$M_2 = \left(\frac{T_2}{T_1}\right)^{1/2} M_1\left\{1 + \frac{F}{(\gamma + 1)}\frac{(M_1^2 - 1)}{M_1^2}\right\}$$

Substitution of the equation for the temperature ratio gives the desired results. A summary of the important relations follows

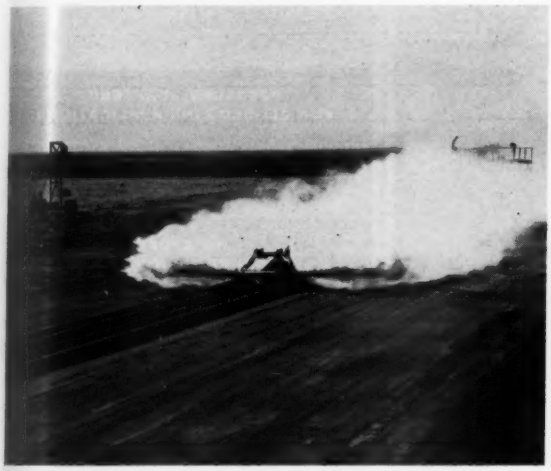
$$\frac{P_2}{P_1} = 1 + \frac{\gamma F}{(\gamma + 1)}(M_1^2 - 1)$$

$$\frac{\rho_2}{\rho_1} = \frac{1}{1 - \dfrac{F}{(\gamma + 1)}\dfrac{(M_1^2 - 1)}{M_1^2}}$$

$$\frac{T_2}{T_1} = \left\{1 + \frac{\gamma F}{(\gamma + 1)}(M_1^2 - 1)\right\}\left\{1 - \frac{F}{(\gamma + 1)}\frac{(M_1^2 - 1)}{M_1^2}\right\}$$

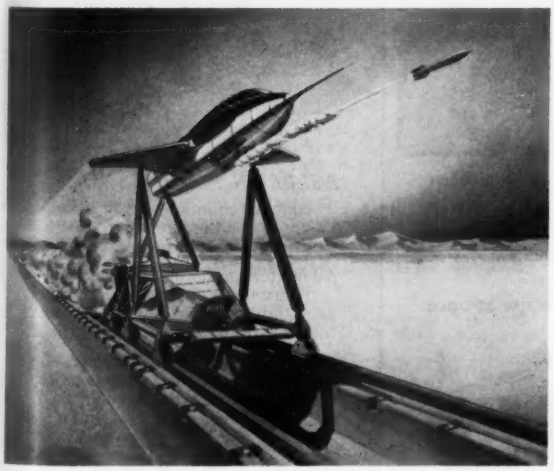
$$M_2 = \sqrt{\frac{(\gamma + 1 - F)(M_1^2 - 1) + (\gamma + 1)}{\gamma F(M_1^2 - 1) + (\gamma + 1)}}$$

where $f = 0$, or, $F = 2$ for a shock wave; $f = 1$, or $F = 1$, for a Chapman-Jouguet detonation wave; and $0 < f < 1$, or $1 < F < 2$ corresponds to a strong detonation wave. It can easily be shown that $f > 1$ corresponds to a weak detonation wave, that case where the heat added must bring the Mach number behind the wave to a supersonic value. This impossible solution is predicted by the previous equations since for $f > 1$, F is imaginary. The solutions for $f < 0$ ($M_1 < 1$) would hold for a deflagration where the flame is thin enough to be considered as a discontinuity, or where the pressure, temperature, density, and velocity are measured far enough in front of and behind the flame so that no gradients exist at these points.



U. S. Navy

Slamming stop . . . . Rocket-propelled sled is slowed down by water brake at the end of a test run. A 10,000-ft long graduated depth water brake trough allows decelerations of 5–30 g's.



U. S. Navy

SNORT in action . . . Secondary firings of projectiles are possible as shown in drawing of small plane facsimile firing missiles. Test carriages plus payloads of 200–20,000 lb are accelerated to speeds of 1000–3500 fps by combinations of rocket motors. Accelerations of 10–100 g's are possible.

Errata

1 "Unconditional Stability of Low-Frequency Oscillation in Liquid Rockets," by Sin-I Cheng, September-October 1954 issue of JET PROPULSION:

(a) Equations [15] should read:

$$N_r = N_{ro}(1/2 + 2K + H) + N_{rf}(1/2 - 2K - H) - K(N_{ro} - N_{rf})\cos\omega - K(N_{io} - N_{if})\omega\sin\omega$$

$$N_i = N_{io}(1/2 + 2K + H) + N_{if}(1/2 - 2K - H) + K(N_{ro} - N_{rf})\sin\omega/\omega - K(N_{io} - N_{if})\omega\sin\omega$$

(*b*) In Equations [19] and [20], $3K$ should be replaced by $-K$, and $-2K$ should be replaced by $+2K$.

2 "Low-Frequency Combustion Stability of Liquid Rocket Motor With Different Nozzles," by Sin-I Cheng, April 1955 issue of JET PROPULSION:

(a) The constant g in the expression of θg following Equation [2.1] should be deleted.

(b) In Equation [3.4], $-2K$ should be $+2K$, and $+2K$ should be $-2K$.

(c) In Equation [3.8] the operator should read

$$1 + \frac{\theta}{2\delta} + b\frac{d}{dz}$$

(d) Equation [3.9] should read

$$(1 + b)\frac{d}{dz}\varphi + (1 - n)\varphi + n\varphi(z - \delta)$$

$$= (2K + H + 1/2)\mu_0(z - \delta) - (2K - 1/2 + H\mu_f(z - \delta) - K\left(1 - 2b\frac{d}{dz}\right)[\mu_0(z - \delta - 1) - \mu_f(z - \delta - 1)]$$

(e) The expression for $b\dfrac{d}{dz}\theta_e$ following Equation [3.9] should read $2k\dfrac{d}{dz}$ [ ].

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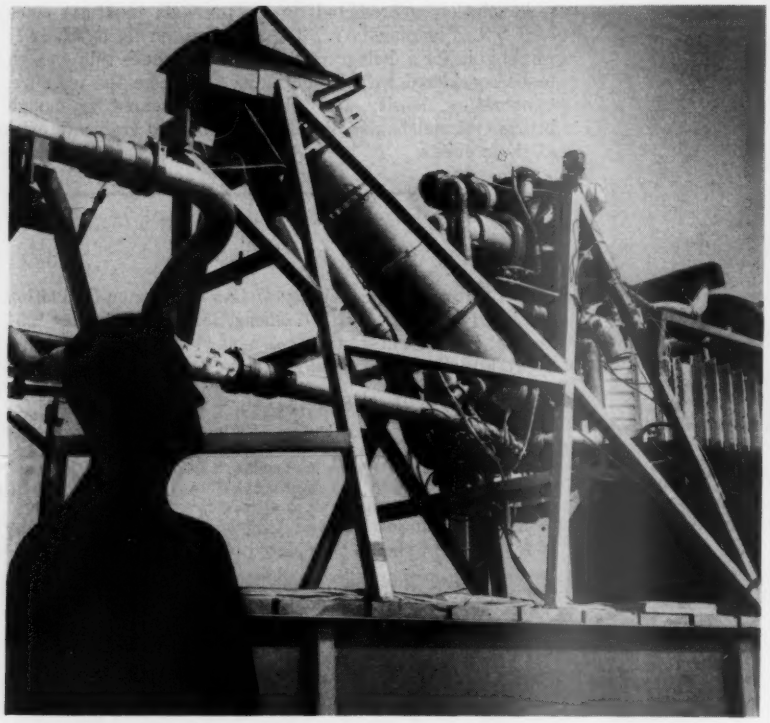

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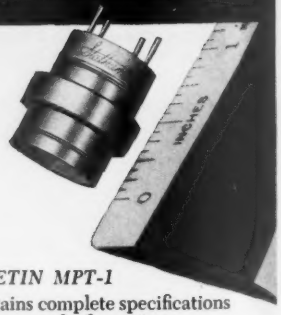
0-5 to 0-150 PSIG . . . MODEL P132



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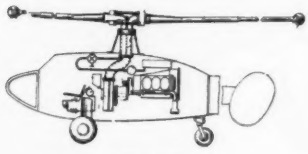
Two-stage power jets and increased flame propagation for helicopters (2,710,067). Kazimir M. S. del Pesaro, Bronxville, N. Y., assignor to Jet Helicopter Corp.



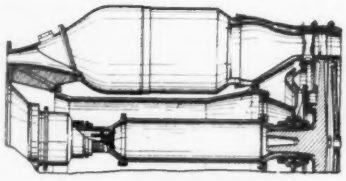
2,710,067

Control of propeller-driving gas turbine engines (2,710,068). Wm. H. Lindsey and Edwin G. Caswell, Coventry, England, assignors to Armstrong Siddeley Motors, Ltd.

Nozzle box attachment (2,710,503). Winnett Boyd, Bobcaygeon, Canada, assignor to A. V. Roe Canada, Ltd.

Gas turbine tail cone (2,710,523). Joseph Thompson Purvis, Toronto, Canada, assignor to A. V. Roe Canada, Ltd.

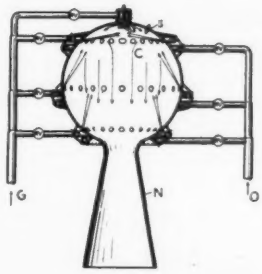
An inner skin slotted axially from a lip sliding in a groove to accommodate circumferential expansion and contraction of the skin.



2,710,503

Zonal spray combustion chamber for rockets and rocket craft (2,709,887). Robert H. Goddard, deceased, late of Annapolis, Md., by Esther C. Goddard, executrix, Worcester Mass., assignor to The Daniel and Florence Guggenheim Foundation.

Spherical combustion chamber fed by sets of ports placed in planes parallel to the chamber axis. Means for reducing the feeding pressure of each set of nozzles in proportion to their distance from the closed end of the chamber.

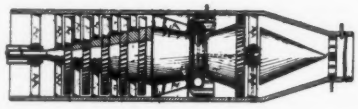


2,709,887

Variable area nozzles for jet propulsion systems (2,709,888). Raymond Holl and Wm. Deacon, Leicester, England, assignors to Power Jets (Research and Development) Ltd.

Gas turbine using revolving ram jet burners (2,709,889). Wadsworth W. Mount, Summit, N. J.

Turbine driven by the exhaust from a ram-jet motor on the periphery of a power-generating wheel for rotating a power output shaft and an air compressor.

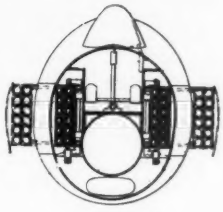


2,709,889

Control system for rocket motor (2,711,751). Henry L. G. Sunley, Coventry, England, assignor to Armstrong Siddeley Motors, Ltd.

Aircraft and armament therefor (2,709,947). Robert J. Woods, Grand Island, N. Y., assignor to Bell Aircraft Corp.

Retractable rack for launching rockets, the tubes arranged for selective firing from any tube. The rack may be moved from a stowed position and disposed entirely in the airstream next to the body, to be clear of the body portion for increased aerodynamic drag effects.

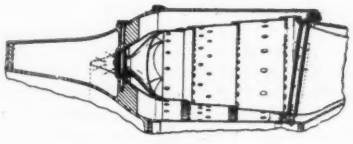


2,709,947

Remote control system with position indicating means (2,709,773). Ivan A. Getting, Belmont, and Lee L. Davenport, Cambridge, Mass., assignors to the War Dept.

A remote control system for controlling the movement of aircraft, and detection means coupled to frequency circuits for rendering the circuits selectively operative.

Flame tube structure for combustion equipment of gas-turbine engines (2,709,894). George Oulianoff and Jeffrey Evans, Alvaston, England, assignors to Rolls-Royce, Ltd.



2,709,894

Mechanism for intermittent feeding of combustion liquids to a combustion chamber in propulsion apparatus (2,709,890). Robert H. Goddard, deceased, late of Annapolis, Md., by Esther C. Goddard, Executrix, Worcester, Mass., assignor to The Daniel and Florence Guggenheim Foundation.

Method of feeding liquid fuel under pressure so that periods of liquid flow and flow interruption are equal and of brief duration.

Valveless resonating jet motor (2,709,891). James Y. Dunbar, Wm. Schubert and Norman R. Hussey, U. S. Navy.

Resonant fluid housing forming an acoustic cavity for a standing wave, and an open conduit for a fluid stream. The housing has a fluid discharge opening which locates a velocity antinode of the adjacent standing wave.

Heat transfer system for aircraft deicing and rotating electrical equipment cooling (2,709,892). Cecil G. Martin, Bedford, Ohio, assignor to Jack & Heintz, Inc.

Rotating electrical machine carried by the housing of an aircraft jet engine having a heat transfer system with a conduit to a liquid coolant system for conveying heat caused by losses of the electrical machine in operation.

Gas turbine apparatus (2,711,070). Frederick W. Henning, Springfield, Pa., assignor to Westinghouse Electric Corp.

Turbojet power plant with fuel injection device mounted on a hollow fairing cone spaced within the combustion chamber to form a diffuser passage for a high velocity air stream.

Arrangement for starting a prime mover by independently driven lubricating pump (2,711,071). Adolph Frankel, Rugby, England, assignor to The English Electric Co.

Combustion chamber fairing (2,711,072). John M. Wetzler, Indianapolis, Ind., assignor to General Motors Corp.

Spaced burners extending axially of the annular casing passages between rows of flow plates dividing the inlet portion into compartments each containing one burner and simulating separate combustion chambers.

Fuel metering apparatus for speed control of gas turbine engines (2,711,073). Allen S. Atkinson, Silver Spring, Md., assignor to one-half to Daniel G. Russ, South Bend, Ind.

Aft frame and rotor structure for gas turbine (2,711,074). Alan Howard, Schenectady, N. Y., assignor to General Electric Co.

Rocket engine (2,711,629). Richard L. Schapker, Cincinnati, Ohio.

Turbine shaft extending into a rocket engine to drive auxiliaries arranged coaxially with the shaft.

Rockets (2,711,630). Sylvester Clyde Lehman, New York, N. Y.

Method and means for increasing airplane pilots' resistance to acceleration forces (2,707,087). Wm. A. Bradley, North Wales, and Reuben Flanagan Gray, Levittown, Pa.

EDITOR'S NOTE: The patents listed above were selected from recent issues of the Official Gazette of the U. S. Patent Office. Printed copies of patents may be obtained at a cost of 25 cents each, from the Commissioner of Patents, Washington 25, D. C.

Boston Sees Nike: Courtesy of ARS

Two soldiers from the 514th Anti-Aircraft Missile Battalion, Squantum, Mass., discuss features of a Nike missile with (*left to right*) James J. Harford, ARS executive secretary; Richard W. Porter, president; Ray Minichiello, chairman for ARS of Boston meeting; and Noah S. Davis, vice-president. Missile was on display in lobby of Hotel Statler throughout meeting.

New England Section Chartered at Boston Meeting

C. LINCOLN JEWETT of Arthur D. Little, Inc., Cambridge, Mass., received the charter for the newly established New England Section from national president Richard W. Porter at a dinner meeting in Boston on June 22. Jewett is president of the Section.

Toastmaster for the dinner, which featured ARS participation in ASME's Semi-Annual Meeting, was Frederick C. Durant, III, also of Arthur D. Little and president of the International Astronautical Federation.

Durant introduced Paul E. Sandorff, associate professor of aeronautical engineering at Massachusetts Institute of Technology, the main speaker.

Satellite Launch from Aircraft?

At the dinner meeting, Prof. Sandorff outlined the advantages of using manned high altitude aircraft as a launching platform for a satellite rocket. Sandorff says that a two-stage, aircraft-launched rocket would have a 60 per cent chance of getting into a satellite orbit, while the all-rocket combination would only be 35 per cent. Cost, too, favors the use of aircraft; the all-rocket design would be about $170 million for 10 satellites, while the same number of aircraft-launched rockets would run about $48 million (plus aircraft operation cost, etc.). Sandorff concludes that while the unmanned satellite is near, the manned space station is not now economically or militarily feasible.

ARS arranged two technical sessions at the meeting, as well as cosponsoring two sessions organized by ASME's Aviation Division.

Liquid Hydrogen Tamed

The properties of hydrogen and newer methods of liquefaction, storage, and field use were reviewed by A. Pastuhov and C. L. Jewett, Arthur D. Little, Inc., Cambridge, Mass. The spontaneous combustion of oxygen-hydrogen mixtures and the effect of the ortho-para hydrogen conversion were treated. A production pilot plant (low pressure) and roadable, refrigerated Dewar system (530-gal capacity) was described. Although experimental liquid hydrogen rocket systems have been in operation for several years, the newer techniques being evolved may allow much wider and safer rocket usage.

Static Testing

Measuring the combustion time lag in a lox-alcohol rocket motor at Princeton was described by Luigi Crocco, Jerry Grey, and George Mathews. A flow modulating unit in each propellant line allowed the phase angle between the two propellant flow rate oscillations at the injector to be varied. The mean total time lag dropped asymptotically from 6 msec to 2 msec as the modulating frequency increased from 40–220 cps.

High frequency response instrumentation for measuring chamber pressure and thrust was described by Jack Buchanan, Thiokol Corp., Huntsville, Ala. Short burning time solid propellant rockets have imposed test problems with regard to accuracy and precision of static tests. Buchanan discussed how these problems are being solved with recording equipment, timing systems, amplifiers and couplers, digitalization, calibration, transducers, and data reduction. Precision in testing will have to keep pace with rocket performance tolerances which are approaching 1 per cent.

Systems Evaluation

Low frequency oscillations ("chugging") of liquid fuel rocket systems were explained by using a feedback-system concept where the dynamics of the fuel supply system is an important factor. Y. T. Li of Massachusetts Institute of Technology discussed the stabilization of such low-frequency oscillations. Two fuel line stabilizers—one a rate-type, the other an inertia-type—were suggested for possible experimental evaluation.

In the design of turbine blades, the influence of rotor speed on torsion frequencies is important. C. E. Danforth, General Electric Co., Evendale, Ohio, evaluated this parameter and found that when the blade thickness dropped below 10 per cent of the chord (with a tip speed of over 1000 ft/sec), the torsional frequency change is significant. The latter item is most useful in evaluating fatigue and characteristics of present systems.

Board Authorizes Monopropellants Committee

AT the June 22 Board of Directors Meeting at the Hotel Statler in Boston, a Committee on Monopropellant Test Methods was approved.

Purpose of the committee will be, according to its Operating Procedures, to "concern itself with recommendation to the rocket industry and related industires of equipment and methods to be used for the determination of characteristic properties of liquid monopropellants."

President Porter designated the following as members:

Three-Year Term: H. F. Calcote, Experiment, Inc.; J. P. Thackeray, Aerojet-General Corp.; W. B. Moen, Air Reduction Co.; P. F. Winternitz, New York University.

Two-Year Term: L. L. Rapp, Reaction Motors, Inc.; P. M. Terlizzi, Naval Air Rocket Test Sta.; J. H. Keefe, Becco Chemical Div., Food Mach. and Chem. Corp.; W A. Cuddy, Wyandotte Chemicals Corp.

One-Year Term: I. Glassman, Princeton University; D. D. Thomas, Mathieson Chemical Corp.; C. H. King, Jr., United Aircraft Co.; F. S. Forbes, Wright Air Devel. Command.

Northwestern President to Open Gas Dynamics Symposium, Aug. 22-24

J. ROSCOE MOORE, president of Northwestern University, will welcome registrants at the first session of the ARS-Northwestern Technological Institute Gas Dynamics Symposium, to be held August 22–24 on the Evanston, Ill., campus.

Also greeting the session will be Richard W. Porter, ARS president.

The program consists of 25 papers in four sessions, as well as three informal luncheons and a banquet on August 23. H. Guyford Stever, Chief Scientist, USAF, will be the banquet speaker.

Theme of the Symposium, which is scheduled to convene biennially, is "Aerothermochemistry." This first Symposium is being conducted with the co-operation of the Office of Scientific Research of the Air Research and Development Command.

Program of Gas Dynamics Symposium

Objectives

THE first Symposium on Gas Dynamics sponsored by the AMERICAN ROCKET SOCIETY and Northwestern University will have as its theme the subject of Aerothermochemistry. The papers to be presented will cover engineering research in this field with extension to fluid dynamics, chemical kinetics, and thermodynamics. The contributions are unclassified and should be of interest to all concerned with basic problems allied to rocket and jet propulsion as well as to high-speed combustion in general.

Abstracts of the papers to be presented at the Symposium will be compiled and will be available at the time of registration. It is planned that the papers and their pertinent discussions will be brought together after the Symposium in a volume of proceedings.

Registration

A form for advance registration has been mailed to all members. Prospective registrants are urged to complete this and return it at their earliest convenience. Early mail registrations will be assured of housing.

A registration fee of $5 will be charged each registrant, which will entitle him to attend all sessions and obtain copies of meeting materials. Authors, session chairmen, and families of registrants will not be asked to the pay the registration fee.

Completion of registration and allocation of University housing will take place after arrival at the Technological Institute. The registration desk in the main lobby of the Institute will be open from 2:00 p.m. to 7:00 p.m. on August 21 and again starting 8:00 a.m., August 22.

Transportation

The Technological Institute can be reached conveniently from air and railroad terminals in Chicago and by Chicago & Northwestern Railroad in Evanston. Direct limousine service to Evanston is available from the airport. Those traveling by train and arriving in Chicago can take Chicago Rapid Transit Systems (Suburban-Elevated) to Howard Street and then ride to Noyes Street Station in Evanston. The Technological Institute is located on Sheridan Road at the corner of Noyes Street, two blocks east of the Elevated station.

Symposium Headquarters

The symposium headquarters will be the Departmental Office of the Department of Mechanical Engineering, Room 280. The telephone is UNiversity 4-1900, Extensions 299 or 220. Correspondence should be addressed to: Gas Dynamics Symposium, Department of Mechanical Engineering, Northwestern Technological Institute, Evanston, Ill.

Housing

Although space is limited, it is believed that all registrants who wish can be housed in modern University dormitories adjacent to the Technological Institute. A package price of $20 has been set to cover the period of the Symposium. This includes dormitory room starting Sunday, August 21, with meals starting at breakfast on August 22 and running through lunch on August 24. The banquet scheduled for August 23 is also included. Those who wish to avail themselves of the dormitory restaurant facilities only, may use these on a per meal basis. Arrangements can be made for spending the night of August 24 in the dormitories at $3 per person, European plan.

Registrants desiring hotel accommodations and those accompanied by families should make reservations directly with any of the following Evanston Hotels: Georgian, North Shore, Orrington, Homestead, or Library Plaza.

Entertainment

Evanston, on the shore of Lake Michigan, offers many opportunities for fun and relaxation. Registrants who wish to combine their scientific pursuits with a vacation may bring their families. Informal entertainment can be made available for families, such as swimming at the private beaches of Northwestern University and visits to the many places of interest, such as the Museum of Science and Industry, the Adler Planetarium, the Chicago Art Institute, concerts, plays, and musicals. Baby sitting can be arranged for upon request.

A banquet is planned for Tuesday night, August 23. It is hoped that registrants and the adult members of their families will attend the banquet. The cost of the banquet (for those not using the room-and-board package plan) is $3.75 per person.

Symposium Committee

Noah S. Davis, Jr., Becco Chemical Div., Food Mach. and Chem. Corp.
Andrew G. Haley, Haley, Doty and Wollenberg
James J. Harford, American Rocket Society
Burgess H. Jennings, Northwestern Technological Institute
Layton C. Kinney, Armour Research Foundation
Donald H. Loughridge, Northwestern Technological Institute
Martin Summerfield, Princeton University
Ali Bülent Çambel, Northwestern Technological Institute

The program follows:

MONDAY, AUGUST 22, 1955

9:00 a.m. Session I

TURBULENT COMBUSTION

Chairman: Ali Bülent Çambel, Northwestern Technological Institute
Welcome: J. Roscoe Miller, President, Northwestern University
Opening Remarks: Richard W. Porter, President, American Rocket Society

Status of Research on the Physics of Turbulent Combustion in Premixed Gases, by Martin Summerfield, Princeton University

Mathematical Theory of Turbulent Flames, by J. M. Richardson, Ramo-Wooldridge Corp.

An Investigation of the Burning Rates of Confined Turbulent Flames, by J. J. Zelinski, W. T. Baker, L. J. Mathews III, and E. C. Bagnall, The Johns Hopkins University

Diffusion Flames, by Itsuro Kimura and Seiichiro Kumagai, University of Tokyo

12:30 p.m. Informal Luncheon

1:45 p.m. Session II

FLAME STABILIZATION

Chairman: Arch C. Scurlock, Atlantic Research Corp.

Experiments Concerning the Mechanism of Flame Blow-Off from Bluff Bodies, by Edward E. Zukoski and Frank E. Marble, California Institute of Technology

Studies of Flow and Mixing in the Recirculation Zone of Baffle Type Flameholders, by A. A. Westenberg, W. G. Berl, and J. L. Rice, The Johns Hopkins University

Aerothermochemical Aspects of Flameholder Performance, by John W. Bjerklie, Marquardt Aircraft Co.

Combustion Performance on Baffle Type Flameholders Located in Jet Engine Diffusers, by Edward P. French, Marquardt Aircraft Co.

TUESDAY, AUGUST 23, 1955

9:00 a.m. Session III

DETONATION AND THERMODYNAMICS

Chairman: Vincent J. Cushing, Armour Research Foundation

Considerations for the Attainment of a Standing Detonation Wave, by J. Rutkowski and J. A. Nicholls, University of Michigan

Review of Recent Work on Strong Shock Waves Done At Cornell University, by R. M. Patrick and A. Kantrowitz, Cornell University

Total Entropy Production in Chemically Irreversible Processes, by Shao-Lin Lee and John F. Lee, North Carolina State College

Some Thermodynamic Properties of C_nH_{2n}—Air Combustion Gases, by H. N. Powell and S. N. Suciu, General Electric Co.

12:30 p.m. Informal Luncheon

1:45 p.m. **Session IV**

LAMINAR FLAMES

Chairman: B. H. Jennings, Northwestern Technological Institute

Theoretical Studies of Laminar Flame Propagation, by S. S. Penner, California Institute of Technology

An Analysis of Flame Propagation Based on Simplified Reaction Kinetics, by E. Mayer and H. Carus, Arde Associates

Burning Velocities by the Bunsen Burner Method, by J. M. Singer, Joseph Grumer, and E. B. Cook, U. S. Bureau of Mines

Study of Pressure Dependence of Burning Velocity by the Spherical Vessel Method, by John Manton, B. B. Milliken, U. S. Bureau of Mines

Studies of the Ignition of Gaseous Hydrocarbons, by C. F. Mozer and R. K. Sherburne, New Mexico College of Agriculture and Mechanic Arts

7:00 p.m. **Symposium Banquet**

Speaker: H. Guyford Stever, Chief Scientist, USAF.

WEDNESDAY, AUGUST 24, 1955

9:00 a.m. **Session V**

NONSTEADY COMBUSTION

Chairman: C. J. Kippenhan, Washington University

Combustion Instability, by Luigi Crocco, Princeton University

Oscillatory Combustion in Rocket Propulsion Engines, by A. O. Tischler and Theodore Male, National Advisory Committee for Aeronautics

Cellular Slot Burner Flames, by G. H. Markstein and D. Schwartz, Cornell Aeronautical Laboratory

Vibration of the Gaseous Column Behind a Strong Detonation Wave, by Boa-Teh Chu; The Johns Hopkins University

12:30 p.m. **Informal Luncheon**

1:45 p.m. **Session VI**

COMBUSTION OF CONDENSED PHASES

Chairman: Noah S. Davis, Jr., Becco Chemical Div., Food Mach. and Chem. Corp.

From Liquid Stream to Vapor Trail, by C. C. Miesse, Aerojet General Corp.

Steady State Burning of a Liquid Droplet with Finite Reaction Kinetics, by Jack Lorell, California Institute of Technology, Henry Wise, Stanford Research Institute, and R. S. Carr, California Institute of Technology

A Study of Radius and Surface Temperature Variations of an Evaporating Liquid Droplet in the Absence of Macroscopic Convection, by S. L. Soo and H. K. Ihrig, Jr., Princeton University

A Theory of the Spread of Flame in a Propellant Bed, by G. P. Wachtell, The Franklin Institute

Connecticut Valley Section Forming

AN organizational meeting was held recently in Meriden, Conn., for the purpose of forming a Connecticut Valley Section of ARS. The Section is planning to serve the Valley area from New Haven up to Springfield, Mass., as well as those members from western and eastern Connecticut who wish to participate.

An initial meeting is being arranged for September. Those interested in participating should contact either Yvonne C. Brill, Research Dept., United Aircraft Corp., East Hartford, Conn., or Chester B. Hayes, Gray Research Laboratories, Manchester, Conn.

Indiana Banquet Hears Porter

"THE ABC of Survival" was the subject of an address given by President R. W. Porter at the annual banquet of the Indiana Section. About 100 persons attended the affair on May 12 in Lafayette, Ind.

Guests were welcomed on behalf of Purdue University by Professor D. C. Clark of the Mechanical Engineering Department.

Dr. Porter, introduced by M. J. Zucrow, Professor of Jet Propulsion and Gas Turbines at Purdue, emphasized the importance of the free world's maintenance of leadership in guided missiles.

The talk was illustrated by slides, and a

SECTION PRESIDENTS

Alabama: JOSEPH WIGGINS, *Thiokol Chem. Corp.;* **Arizona:** CHAS. J. GREEN, *Hughes Aircraft Co.;* **Central Texas:** B. S. ADELMAN, *Phillips Petroleum Co.;* **Chicago:** V. J. CUSHING, *Armour Research Foundation;* **Cleveland-Akron:** W. T. OLSON, *NACA;* **Detroit:** FRED KLEMACH, *Natl. Research & Development Corp.;* **Florida:** R. S. MITCHELL, *Pan American World Airways;* **Fort Wayne:** NORMAN BAKER, *Indiana Technical College;* **Indiana:** A. R. GRAHAM, *Purdue Univ.;* **Maryland:** W. G. PURDY, *Glenn L. Martin Co.;* **National Capital:** E. C. PAGE, *Page Communications, Inc.;* **New England:** C. LINCOLN JEWETT, *Arthur D. Little, Inc.;* **New Mexico-West Texas:** R. C. SHERBURNE, *New Mexico A & M;* **New York:** C. W. CHILLSON, *Curtiss-Wright Corp.;* **Niagara Frontier:** T. ZANNES, *Bell Aircraft Corp.;* **Northeastern New York:** A. H. FOX, *Union College;* **Northern California:** M. A. PINO, *California Research Corp.;* **Pacific Northwest:** R. M. BRIDGFORTH, *Boeing Airplane Co.;* **Princeton Group:** IRVIN GLASSMAN, *Princeton Univ.;* **St. Louis:** NORTON B. MOORE, *McDonnell Aircraft Corp.;* **Southern California:** C. M. MCCLOSKEY, *ONR;* **Southern Ohio:** W. J. MIZEN, *Bendix Aviation Corp.;* **Twin Cities:** J. J. SCHONS, *Univ. of Minnesota.*

ARS MEETINGS CALENDAR

Aug. 22–24	ARS-Northwestern University, Gas Dynamics Symposium, Evanston, Ill.
Sept. 19–21	ARS Fall Meeting, Los Angeles, Calif.
Nov. 13–18	ARS-ASME Annual Convention, Chicago, Ill.
Dec. 12–16	Nuclear Science and Engineering Congress, Cleveland, Ohio

Abstracts should be submitted to the Program Chairman, American Rocket Society, 500 Fifth Ave., New York 36, N. Y., six months prior to the meeting date.

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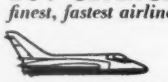

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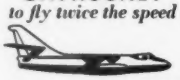

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recently declassified movie of "V-2 Firings from the Aircraft Carrier Midway" were shown.

Arizona Elects Green

CHARLES J. GREEN, engineer at Hughes Aircraft Co., Tucson, is the new president of the **Arizona** Section, succeeding Robert H. Hansen.

Serving under Green will be Edward S. Forman, vice-president; W. J. Peterson, secretary; and Robert F. Roney, treasurer. Directors are Edward J. Meyer, Joel Singer, and Robert M. Shuman.

Plans for Philadelphia Section

SPYROS DAOUSSIS, engineer employed by the Government and Industrial Division, Philco Corp., Philadelphia, is heading a committee which plans to start a **Philadelphia** Section in the Fall. Mr. Daoussis can be contacted at Dept. 12-651, Philco Corp.

140 Hear Stapp

A DINNER meeting of the **Southern California** Section, held at the Pasadena Athletic Club on May 19, featured Lt. Col. John P. Stapp.

The well-known aeromedical expert, who has endured countless acceleration and deceleration tests on rocket sleds, gave a talk on his experiences and showed films.

Romick on Space Travel

A SLIDE-illustrated talk on "The Dawn of the Age of Space Travel" was given by Darrell C. Romick of Goodyear Aircraft Corp., at a May 25 meeting of the **Chicago** Section.

Romick, a member of the ARS Space Flight Committee and author of many papers on the subject, outlined the objectives of space flight and the progress to achieve it.

Aviation Week Editor Speaks on ICBM

ABOUT 200 people attended a June 10 meeting of the New York Section to hear David A. Anderton, Senior Engineering Editor of *Aviation Week*, talk on intercontinental ballistic missiles.

Introduced by President C. W. Chillson, Anderton discussed possible ballistic paths of the ICBM, as well as problems in aerodynamic heating, guidance, and propulsion. He pointed out the almost complete lack of aerodynamic information in the hypersonic speed range which the ICBM would inevitably reach.

Section Publication Discussed

THE **New Mexico-West Texas** Section devoted its May meeting to a review of experiences with the publication of "Missile Away!"

The editor, Harry Stine, and business manager, John Piech, explained how the magazine functioned and invited the members' participation in it.

Lou Stecher, program chairman, moderated the discussion.

Fort Wayne Section Chartered

BY-LAWS for a proposed **Fort Wayne** Section have been submitted to the ARS Membership Committee and approved. The Section received its charter at an Aug. 9 meeting from V. J. Cushing, **Chicago** Section president.

The Section is already publishing a newsletter, "Rocketry," which includes national as well as local items.

Those interested in joining this Section should contact Norman L. Baker, Indiana Technical College, Fort Wayne.

Swanson speaks to Fort Wayne Section

By-Laws for the new Fort Wayne Section have been approved by the ARS Membership Committee.

The Section is composed principally of students at Indiana Technical College. A May 12 meeting was held at which the principal speaker was Conrad Swanson of the Ordnance Missile Laboratories, Redstone Arsenal (seated, center). Others in the photo include (seated, left to right): Leon Bakow, director; Lloyd Wadekamper, vice-president; Norman L. Baker, president; Marion Stults, director. Standing are: Warren Couture, secretary; Ned Nischwitz, Roger Kammeyer, and Rex Pierson, Jr., directors; and Michael Katanik, treasurer.

Book Reviews

C. F. Warner, Purdue University, Associate Editor

Smithsonian Physical Tables, Volume 120, edited by W. E. Forsythe, Smithsonian Institution, Washington, D. C., 1954, 827 pp. $9.

Reviewed by C. F. Warner
Purdue University

In the 901 separate tables comprising the ninth revised edition of the Smithsonian Physical Tables, Volume 120, are presented data deemed to be of use to physicists and engineers. No attempt is made here to judge the validity of the data or the choice of material presented; however, this reviewer believes that the tables are of such general interest and usefulness that an outline of the subject matter will be of value.

The subject material presented may be subdivided into the following general divisions: (1) units of measurement and unit conversion tables; (2) mathematical functions and tables; (3) constants for temperature measurement including thermocouple reference tables and spectral intensities; (4) photometric data including the emissivities of many materials; (5) temperature characteristics of materials including the thermal conductivity; (6) thermodynamic properties including pressure, volume, and weight relations of gases and vapors; (7) physical and mechanical properties of materials; (8) acoustics; (9) various electrical characteristics of materials including magnetic properties; (10) optics and optical properties of materials; (11) atomic and nuclear data; and (12) miscellaneous data.

Over seventy tables of astronomical and astrophysical data of interest to the space scientist are presented.

Titanium in Industry, by S. Abkowitz, J. Burke, and R. Hiltz, Jr., D. Van Nostrand Co., Inc., New York, 1955, 224 pp. $5.

Reviewed by George F. Kappelt
Bell Aircraft Corporation

"Titanium in Industry" might better have been entitled "The Titanium Industry," for it reviews not only the use of titanium in industry but also the history, production techniques, physical metallurgy, joining, fabricating, metallographic techniques, and finally, almost insignificantly, the use of titanium in industry.

In essence, this volume covers all of the presently accepted current-day knowledge of titanium and its industry. One minor criticism might be offered of this volume, namely, there are still many phases of the alloy development program in current use today that are only briefly mentioned or omitted. This results from the fact that, although the authors have indicated that they have taken every opportunity to re-edit the book based upon current or last-minute information, the preparation of material and printing does consume time and the titanium industry has moved ahead in that time.

The history of the industry and production methods are informative and interesting. They show why titanium is a high-priced material and is destined to remain there with today's batch processing units. A thorough treatment of the ABC's of heat treatment (alpha, beta, or a combination of alpha and beta) is given. This aids in an understanding of the effect of alloy additions—interstitial or substitutional.

The title, "Analytical Technique Section," is somewhat misleading in that the generally accepted methods are stated for each element but no detailed procedures are outlined. For this section to be useful, one must be a competent chemist with a thorough knowledge of analytical procedures. As might be expected, most of the applications given are military uses. The reasons for this are obvious if one goes back and re-evaluates the data given by the authors in Chap. I on the growth of the industry.

This book should appeal to the layman or interested technical worker who has not been indoctrinated into the titanium industry. It does offer a working understanding of the titanium industry and is sufficiently referenced to let the serious reader investigate specific details further.

The Sun, edited by G. P. Kuiper, University of Chicago Press, 1953, 745 pp. $12.50.

Reviewed by S. F. Singer
University of Maryland

The present volume, which deals with all aspects of the sun, is made up of contributions from 23 distinguished astronomers and astrophysicists. The material has been thoroughly edited and integrated by Professor G. P. Kuiper of Yerkes Observatory, one of the world's leading astrophysicists. Three further volumes are planned in this series, dealing with the earth, the other planets, the satellites, the comets, and the smaller bodies of the solar system. There is no doubt that the complete set will constitute the most authoritative and comprehensive treatment of our knowledge of the solar system.

The first section of the present volume is an introduction by Professor L. Goldberg, Director of the Michigan Observatory, giving a historical background to solar research and outlining the chief problems of the sun and its atmosphere. The second section by Professor B. Strömgren, Director of Yerkes Observatory, discusses the sun as a star, including theoretical models of the solar interior. Section three is one of the longest and deals with the solar photosphere, the bright solar layer which gives us the visible light. Professor M. Minnaert, Director of Utrecht Observatory, Holland, discusses in great detail the solar continuous radiation and the Fraunhofer absorption lines. The fourth section written by Dr. Charlotte E. Moore, National Bureau of Standards, is devoted to the identification of spectral lines of the sun. Another major section of the book is devoted to the chromosphere and the corona and is written by Professor H. C. van de Hulst of the Observatory of Leiden, Holland. The ultraviolet and x-radiation originates in these outer regions of the sun's atmosphere.

In the sixth section Professor K. O. Kiepenheuer, Director of the Fraunhofer Observatory, Germany, discusses various aspects of solar activity, a subject of great importance because of the effects on the earth's atmosphere and on the earth itself. After a review of sun spots, solar flares and prominences, Dr. Kiepenheuer discusses the electromagnetic and corpuscular radiations issuing from the sun during periods of solar activity and the resultant terrestrial effects: radio-fadeouts, magnetic storms, and cosmic ray effects. A separate section written by Drs. J. L. Pawsey and S. F. Smerd, of the Radiophysics Laboratory, Sydney, Australia, is devoted to radio emission from the quiet and disturbed sun. The importance of the effects discussed in this section and in the preceding one relates to radio communication and long distance control of missiles.

Section eight is a theoretical treatment of solar electrodynamics by Professor T. G. Cowling of the University of Leeds, England. He reviews basic phenomena and theories for explaining the magnetic field of the sun, the sun spots, and solar flares.

The final section is given over to a description of empirical problems and equipment for studying the sun. Of particular interest are the measurements of the solar spectrum in the ultraviolet region from high altitude rocket observations, as discussed by Dr. R. Tousey of the Naval Research Laboratory.

The book is written so as to be intelligible to the nonspecialist who is versed in the physical sciences. It is also of great value as a reference volume about the sun. The discussion is descriptive for the most part, and there are many illustrations and photographs and over 1000 references to the literature.

Sonics, by Theodore F. Heuter and Richard H. Bolt, John Wiley & Sons, Inc., New York, 1955, 456 pp. $10.

Reviewed by R. C. Binder
Purdue University

The word "sonics" refers to the technology of sound as applied to problems of measurement, control, and processing. The entire frequency range is covered, from audible sounds to ultrasonics (vibrations above the limit of human hearing). Sound waves can be used to penetrate many solids and liquids. Sound can be employed to detect a crack deep in some metal. Sound can be used to measure elastic constants of solids, and to determine the molecular structure of many liquids. Sound can be used in underwater

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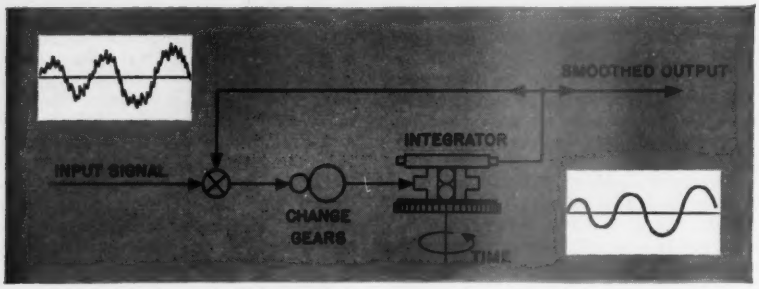

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This reaction, however, is not instantaneous. It occurs after a certain time-lag which may be adjusted by the gear ratio. If the signal is of brief, random nature, the time-lag of the integrator will prevent its acting on the system. On the other hand, a permanent change in the signal will displace the carriage and change the output of the system.

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signaling and in process-control devices. Sound waves can be used to coagulate suspended particles in gases and to disperse suspended particles in liquids. There are countless mechanical, electrical, chemical, and biological applications of sound. This field of sonics is rapidly opening up. Many new uses are being discovered and developed.

This book is the first to present a modern, organized treatment of material in this field. Chapters cover the fundamental physics of vibration and sound, radiation, design principles of electroacoustic and fluid-dynamic transducers, piezoelectric transducers, magnetostrictive transducers, physical mechanisms for sonic processing, devices and techniques for sonic processing, principles of sonic testing and analysis, and acoustical relaxation mechanisms in fluids. The treatment is practical, and is as simple as possible. The physics is given with plausibility arguments rather than with rigorous derivations. The meter-kilogram-second system of units is used throughout. A large number of tables and design curves are presented, which are useful for engineering cases. Material is drawn from physics, engineering, and electronics. Emphasis is placed on the techniques and instrumentation for tackling actual industrial problems. Typical examples are given which illustrate operating principles, and suggestions are made for applications in a variety of fields.

The authors have done an excellent job of digging out information and unifying the presentation. This book is highly recommended for anyone who has or might have any contact with this field.

Modern Physics for the Engineer, edited by Louis N. Ridenour, McGraw-Hill Book Co., Inc., New York, 1954, 500 pp. $7.50.

Reviewed by H. S. SEIFERT
Ramo-Wooldridge Corporation

This book is the outgrowth of a series of lectures given at the University of California for the purpose of acquainting engineering students with recent developments and concepts in modern physics, in the hope that the lag between the discovery and the application of these ideas could thereby be shortened. While the book is not a comprehensive, continuous whole, as indeed it could not be, since it is a collection of nineteen chapters by as many different authors, it omits no currently significant topic of fundamental or applied physics. Emphasis is placed on nuclear physics, the solid state, astrophysics, geophysics, electronics, and information theory.

The impact on the reader is stimulating, since the essential ideas of many fascinating fields are presented concisely and permit him to comprehend with great economy of effort. Nineteen well-qualified authorities, fifteen of them from the West coast, have endeavored to distill the essence of their knowledge and experience, discarding irrelevant and tedious detail. On the whole, they have succeeded in making a very readable and understandable text. In many instances, the concepts cannot be convincingly developed in the few pages available, but for those whose curiosity is piqued, a list of select references is given. The volume forms an admirable source-book for the busy engineer.

A tabulation of topics will give an appreciation of the scope of the book: Introduction; 1 Relativity and the foundations of mechanics. 2 Atomic structure. 3 Physics of the solid state. 4 Magnetism. 5 Microwave spectroscopy. 6 Nuclear structure and transmutation. 7 Electronuclear machines. 8 The actinide elements and nuclear power. 9 Elementary particles. 10 Astrophysics. 11 High-pressure phenomena and geophysics. 12 The earth beneath the sea. 13 Thunderstorms and lightning strokes. 14 Transient phenomena in supersonic flow. 15 Electrons and waves. 16 Semiconductor electronics. 17 Communication theory and transmission of information. 18 Computing machines and the processing of information.

This book can best be appreciated by a reader who is solidly grounded in classical physics. The mathematical background required is moderate, although the concepts in Chaps. 1 and 17 are somewhat abstruse. The reviewer commends the volume especially to workers in the rocket and missile fields, where the demand for versatility in modern physical techniques is particularly pressing.

Falk's Solutions, fourth edition, by Karl H. Falk, Columbia Graphs, Columbia, Conn., 1955, 419 pp. $6.

Reviewed by C. F. WARNER
Purdue University

In this fourth edition of "Falk's Solutions" are presented 400 full-page graphical solutions of the less complicated equations of physics, mechanics, mensurations, etc., most frequently encounted by the engineer and technician. Each page is devoted to the graphical solution of one equation. An illustrative example is given for each problem covered, together with the basic equation that has been used in constructing the graph. Wherever practicable, the equation has been solved repeatedly for each of the variables in turn.

The section devoted to mechanics contains 175 graphs giving the solution to such problems as simple levers, beams, safe beam loads, simple beam deflections, linear thermal expansion, section moduli of common shapes, bolt loads, forces, and static hydraulics.

The areas, volumes, and pertinent dimensions of common shapes and solids are given in the mensuration section. Numerous charts for the conversion from one set of units to another are also included in this section.

One advantage of the graphs is that the results of variations in one or more of the pertinent parameters upon the value sought is readily apparent. This characteristic may save much time and labor when first approximations are being sought for preliminary design purposes.

Rocket Propulsion, by E. Burgess, Chapman and Hall, Ltd., London; Macmillan Co., New York, 1954, 235 pp. $4.50.

Reviewed by D. G. ELLIOTT
Purdue University

This second edition of "Rocket Propulsion" is basically unchanged from the first edition reviewed in the *Journal of the American Rocket Society*, vol. 23, July-August, 1953. The occasional errors of the first edition have been corrected, and some additional and more recent material has been interpolated.

"Rocket Propulsion" remains one of the few nonmathematical books on rockets and space flight which concentrates on propulsion, rather than astronomy. Although written in verbal, rather than mathematical, terms, the book assumes some engineering training on the part of the reader.

The first chapter presents the basic principles of rocket propulsion, and the next three chapters, occupying half of the book, discusses propellants, motors, and feed systems. The following three chapters deal with flight control, long-range rockets, and interplanetary flight. The final chapter discusses briefly the application of nuclear energy to rocket propulsion, and the appendices sketch the derivations of some equations for nozzle flow and for rocket motion.

This book is written in an interesting and unhurried style, yet its two hundred pages encompass a remarkably detailed exposition of rocket propulsion and its applications. Although necessarily based on unclassified and out-of-date material, "Rocket Propulsion" succeeds, with only occasional misleading passages, in presenting a sound and accurate picture of its subject.

Development of the Guided Missile, second edition, by Kenneth W. Gatland, Philosophical Library, Inc., New York, 1954, 292 pp. $4.75.

Reviewed by G. P. SUTTON
North American Aviation, Inc.

This book is a second edition and has been completely revised and expanded. The chapter on propulsion discusses the basic concepts and problems associated with this field, and the research and development chapter delves into rocket models, data and test techniques, and test facilities. Advantages, disadvantages, initial development, and possible guiding control systems for the guided bomb are covered in another section, followed by a presentation of the problems of the long-range missile and a description of the evolution of present-day missiles. The survey of Russian potentialities for long-range rocket development is timely. Details of the telemetering equipment used in British missiles have been added to the appendix.

The original sections have been refined and brought up to date. The new armament section discusses various aspects of missile use against jet bombers, types of missile control and means of defense against missiles. The development problems, existing limitations, and possible homing devices for the air-to-air missile are presented in the following chapter. The sections on rockets for high-altitude research, space-satellite vehicles, and interplanetary flight touch on the basic theories, considerations, and configurations of these missiles and demonstrate the theoretical practicability of space flight. Of

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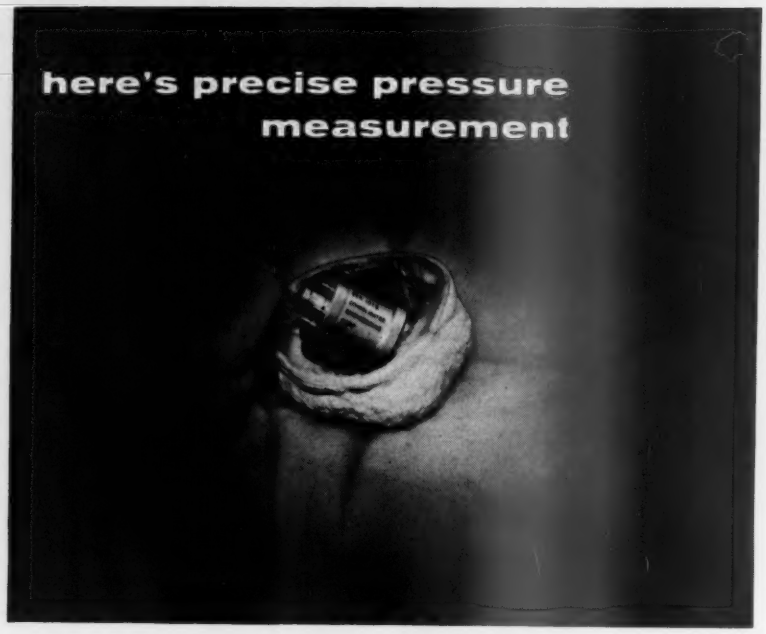

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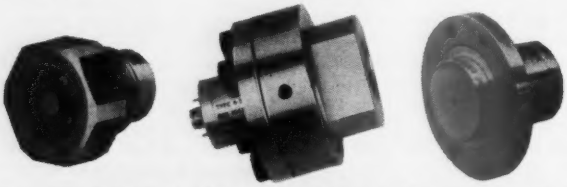

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concern to all of us is the effect of space travel on mammals, which is also discussed herein. In particular, the comparison illustrations of missiles from various countries, reproduced to scale, and the table summarizing available information on significant powered missiles are of current interest. Once again, as with the first edition, the contrast between the sketchy information on British development and the detailed information on American rockets and missiles is indeed amazing. The second edition adds relatively little to the material which had been previously presented on British development, and the American programs seem to be the main source of information for the author.

Because of its many simplified sketches and descriptions, the good selection of photos, and the current material it contains, this book is recommended as good background material for the nontechnical man who wishes to become acquainted with the field of rocketry, past and present. The technical man should find it useful as a historical reference.

Menschen im Weltraum, by Hermann Oberth, Econ Verlag, Dusseldorf, 1954, 256 pp. $6.

Reviewed by ALFRED J. ZAEHRINGER
American Rocket Company

This book—"Space Man"—may be considered as an extension, although not the long-awaited second edition, of Oberth's "Wege zur Raumschiffahrt" first published in 1929. In the period of time between these two works, the ideas and theories laid down in the 1929 work have become commonplace in rocketry and the field of astronautics. In semitechnical style Oberth again attempts to presage the future. All the mathematics is relegated to an appendix and the book starts by outlining a three-stage satellite rocket of truly great proportions—3500 tons—with a payload of 33 tons! Despite its large dimensions—approximately four times the size of the V2—one interesting feature is the use of a low-cost solid propellant booster stage delivering over 70 million lb sec of impulse. In subsequent chapters the author ventures even further beyond present engineering realms to discuss space suits, space stations, space telescopes, space mirrors, electrical space ships, moon autos (Detroit please note!), and the philosophical aspects of space flight. Although the practical engineer will doubtless disagree with much that is outlined in the book, it is hard to see how the imagination of even the most pessimistic attackers of astronautics cannot help being stimulated. If the next twenty-five years show as much rocket progress as did the past twenty-five, this book will have provided a glimpse into our future in space.

Book Notices

Bibliography and Index on Dynamic Pressure Measurement, by W. B. Brombacher and T. W. Lashof, National Bureau of Standards Circular 558, Government Printing Office, Washington, D. C., 1955, 124 pp. $0.75.

The Bibliography lists 850 references on dynamic pressure measurement and, in less

detail, related subjects such as static pressure measurement, and general information on the components of pressure measuring instruments. An index by subject matter and by authors adds materially to the value of the bibliography.

Transistors and Their Applications, a Bibliography, Technological Institute Library of Northwestern University, Evanston, Ill., 1954, 77 pp.

The Bibliography contains over 800 references compiled by students using the facilities of the Technological Institute Library. References are arranged by year of publication and by author.

The Dynamic Theory of Gases, 4th edition, by Sir James Jeans, 1925, reprinted by Dover Publications, Inc., New York, 1954, 444 pp. $2.

This book is a new inexpensive, unabridged edition of the classic treatise on gases. The engineer and physicist will find this a welcome addition to their reference library.

Atoms for Peace, by D. O. Woodbury, Dodd, Mead and Company, New York, 1955, 257 pp. $3.50.

An interesting presentation of the subject of atomic energy by a non technical writer for the general public. Interesting reading for the nontechnical public.

The following publications may be obtained from the Superintendent of Documents, G. P. O., Washington, D. C.:

Table of Sine and Cosine Integrals for Arguments From 10 to 100, Applied Mathematics Series no. 32, National Bureau of Standards, 1954, 187 pp. $2.25.

Table of the Gamma Function for Complex Arguments, Applied Mathematics Series no. 34, National Bureau of Standards, 1954, 105 pp. $2.

Table of Salvo Kill Probabilities for Square Targets, Applied Mathematics Series no. 44, National Bureau of Standards, 1954, 33 pp. $0.30.

Tables of Functions and of Zeros of Functions, Applied Mathematics Series no. 37, National Bureau of Standards, 1954, 210 pp. $2.25.

Tables of the Error Function and Its Derivatives, Applied Mathematics Series no. 41, National Bureau of Standards, 1954, 302 pp. $3.25.

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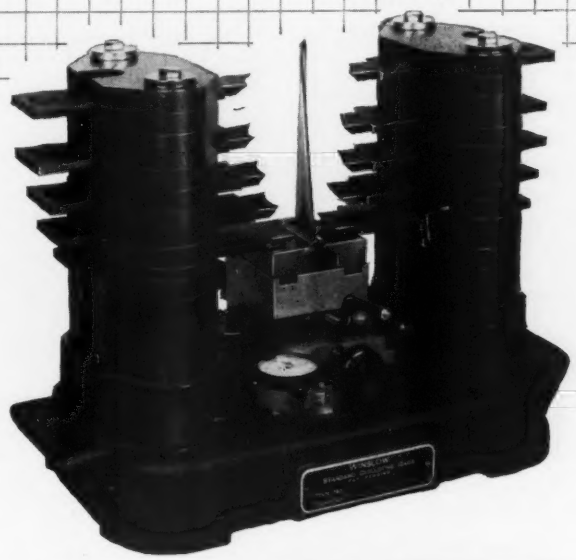

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Jet Propulsion Engines

The Design of Power Plant Ducting, by H. S. Fowler, *Canada Nat. Res. Counc. Rep.* no. ME-208, May 11, 1954, 71 pp.

The Future of the Small Industrial Gas Turbine, *Oil Engine and Gas Turbine*, vol. 22, Mar. 1955, pp. 433–434.

Lodge Igniters for Gas Turbines, *Oil Engine & Gas Turbine*, vol. 22, Mar. 1955, pp. 435–436.

How Marquardt Backs up Ramjet Development Work, Part 2, by Irving Stone, *Aviation Week*, vol. 62, Apr. 25, 1955, pp. 53–54.

The First 100 Years of Aircraft Powerplants, by P. B. Taylor, *SAE J.*, vol. 63, Feb. 1955, pp. 89–96.

Bristol's B.E. 25 Turboprop, by S. G. Hooker, *Aeroplane*, vol. 88, Apr. 29, 1955, pp. 563–565.

Rocket Propulsion Engines

Rocket Power for Helicopters, by Erik Bergaust, *Aero Digest*, vol. 70, Apr. 1955, pp. 32–40.

Heat Transfer and Fluid Flow

Review of Experimental Investigations of Liquid-Metal Heat Transfer, by Bernard Lubarsly and S. J. Kaufmann, *NACA TN* 3336, Mar. 1955, 115 pp.

Turbulent Heat Transfer Measurement at a Mach Number of 2.06, by M. J. Brevoort and Bernard Rashis, *NACA TN* 3374, Mar. 1955, 20 pp.

One-Dimensional Calculation of Flow in a Rotating Passage With Ejection Through a Porous Wall, by E. R. G. Eckert, J. N. B. Livingood, and Ernst I. Prasse, *NACA TN* 3408, Mar. 1955, 29 pp.

A Theory for Predicting the Flow of Real Gases in Shock Tubes With Experimental Verification, by Robert L. Trimpi and Nathaniel B. Cohen, *NACA TN* 3375 Mar. 1955, 69 pp.

Fluid Mechanics Studies—Transition Phenomena in Pipes and Annular Cross Sections, by R. S. Prengle and R. R. Rothfus, *Indust. Engng. Chem.*, vol. 47, Mar. 1955, pp. 379–386.

Flow of Fluids, by Murray Weintraub, *Indust. Engng. Chem.*, Part 2, vol. 47, Mar. 1955, pp. 558–?

On Turbulent Jet Mixing of Two Gases at Constant Temperature, by S. I. Pai, *J. Appl. Mech.*, vol. 22, Mar. 1955, pp. 41–47.

Summary of Recent GALCIT Hypersonic Experimental Investigations, by Henry T. Nagamatsu, *J. Aero. Sci.*, vol. 22, Mar. 1955, pp. 165–172.

On Unsteady Flow Through a Cascade of Airfoils, by L. C. Woods, *Proc. Roy. Soc. Lond.*, vol. 228, Feb. 1955, pp. 50–65.

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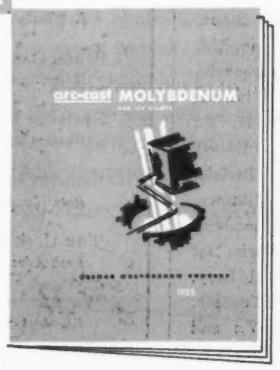

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Working at Princeton's Guggenheim Jet Propulsion Center will be Richard Levy, Princeton, N. J.; Gerald N. Rosen, Teaneck, N. J.; Daniel Rosner, Bronx, N. Y.; and Donald R. Willis, Warwickshire, England. Rosen is a member of ARS.

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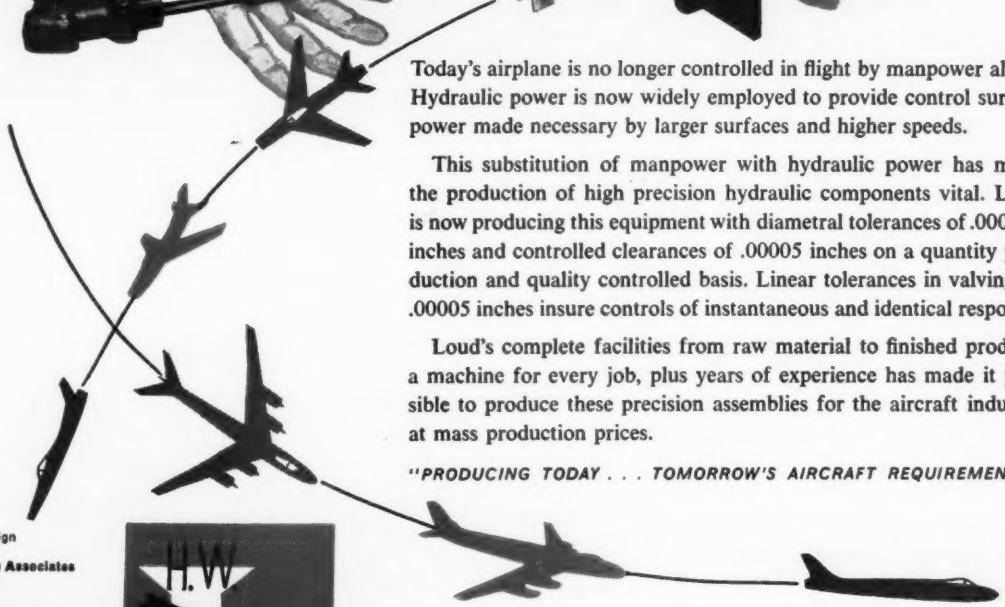

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